DESY SUMMER STUDENT LECTURES

JULY 28, 2008

Universität Hamburg

Free-Electron Laser

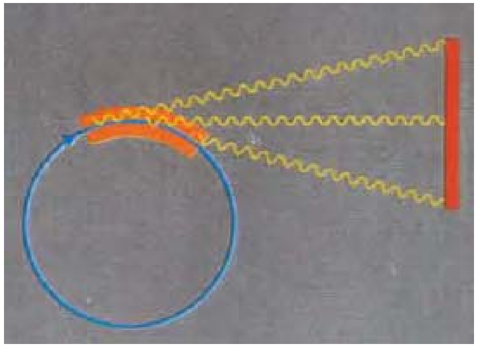
Jörg Rossbach

University of Hamburg & DESY, Germany

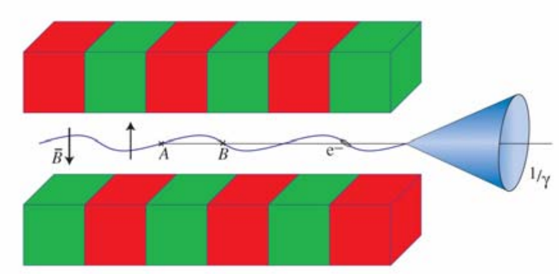
- Motivation & Basics
- Technology
- Results

email: joerg.rossbach@desy.de

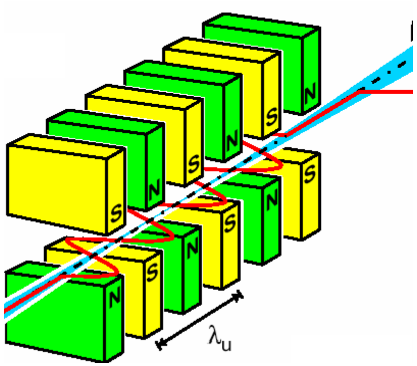
Electron Accelerators as Light Sources

a) 

Electron storage ring with bending magnets:
- continuous spectrum
- wide angular distribution

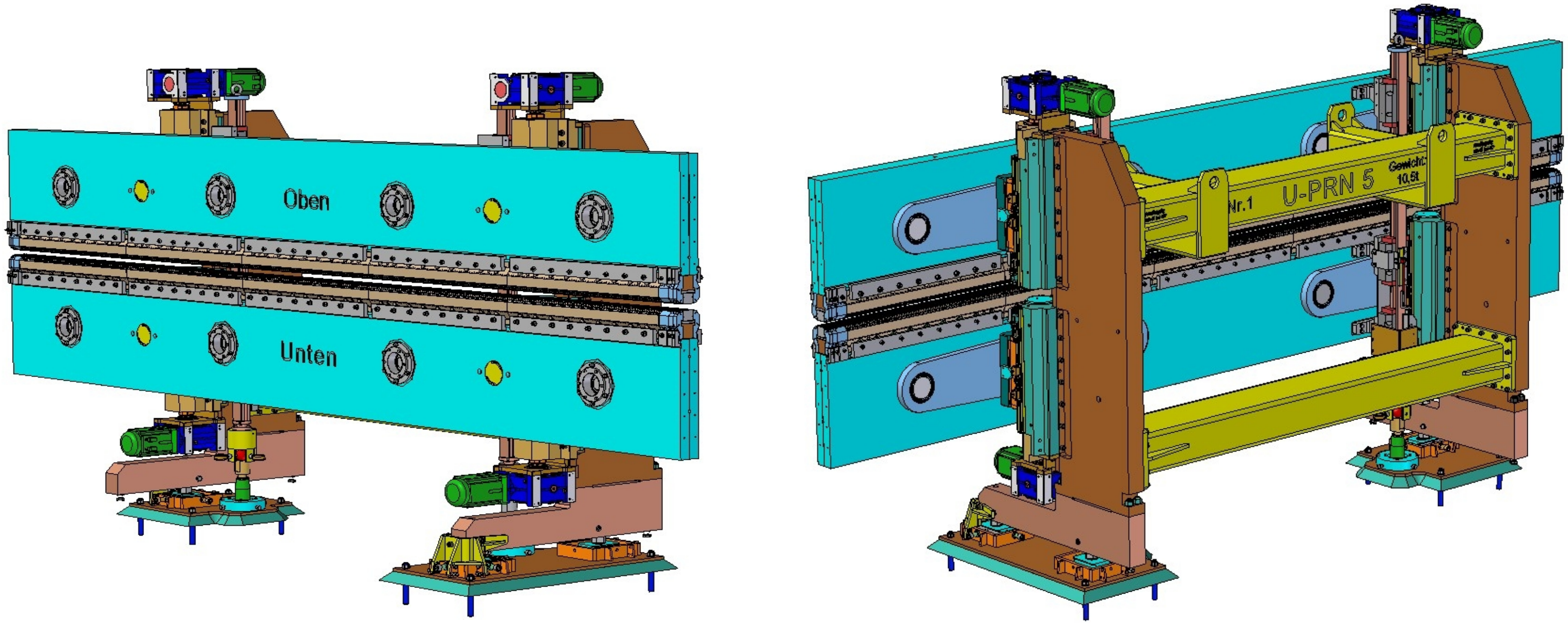
b) 

Undulator radiation:
- (almost) monochromatic
- narrow angular distribution

c) 

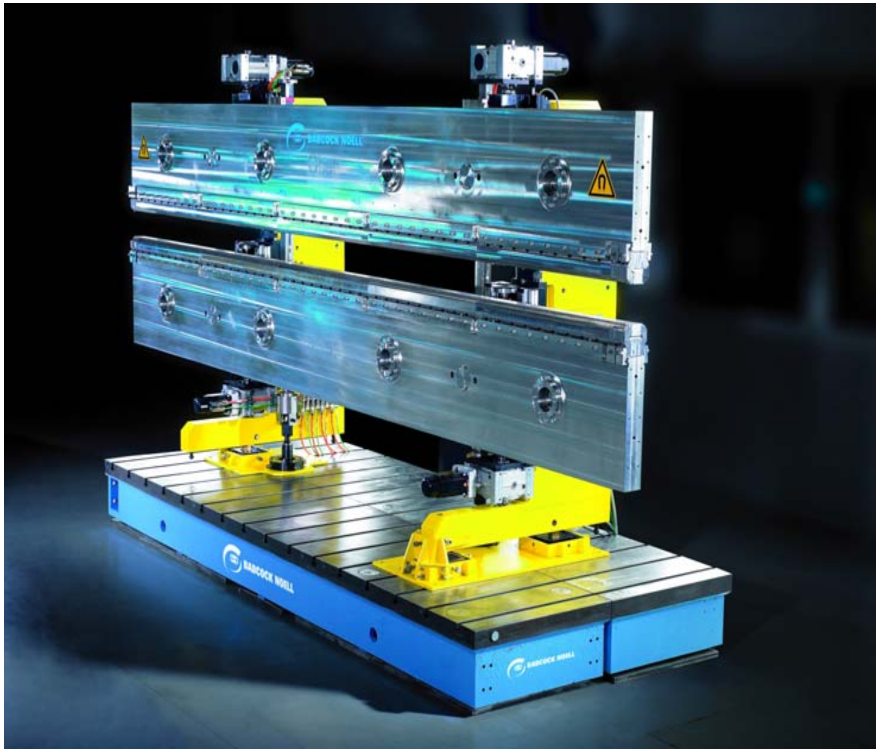
Free-Electron Laser (FEL):
- narrow spectral line
- transverse coherence
- powerful: $I_N = N^2 \cdot I_1$

Undulators with Variable Gap for XFEL



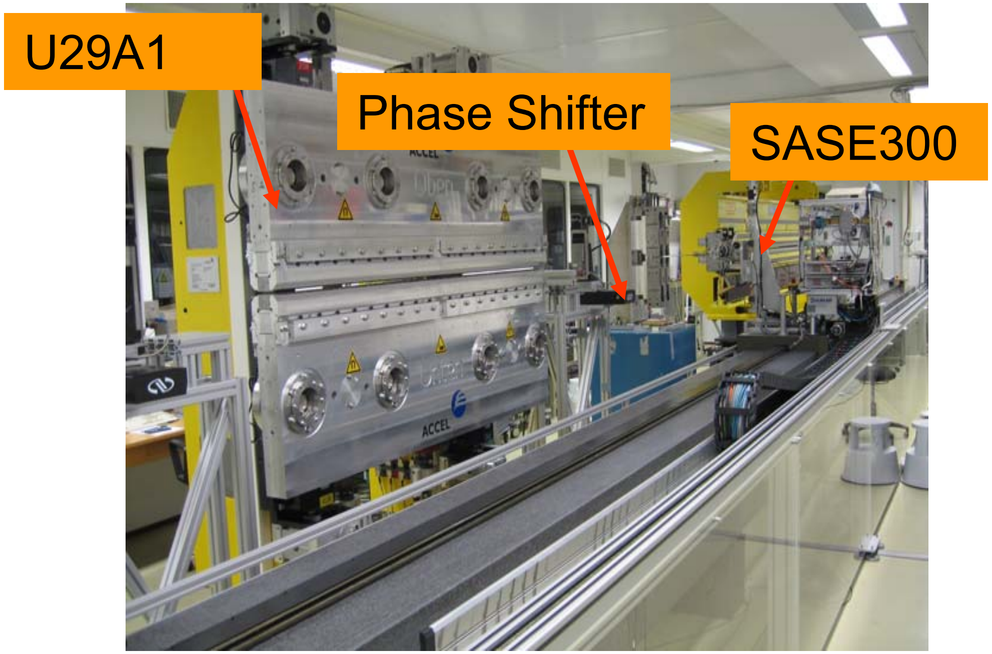
Challenge:
Guarantee reproducibility of gap size at micrometer precision !

Prototype Undulators for XFEL

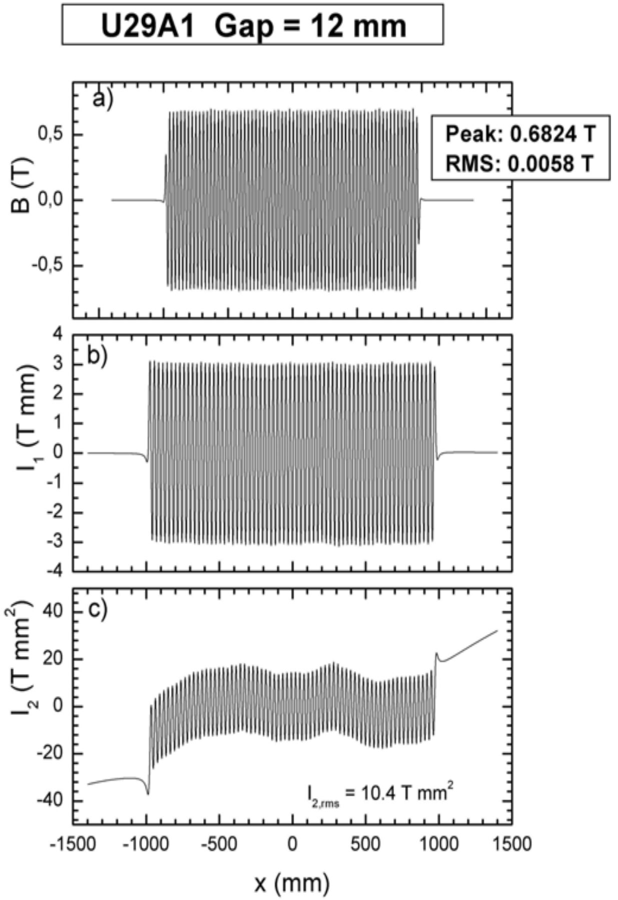


5 m **2 m**

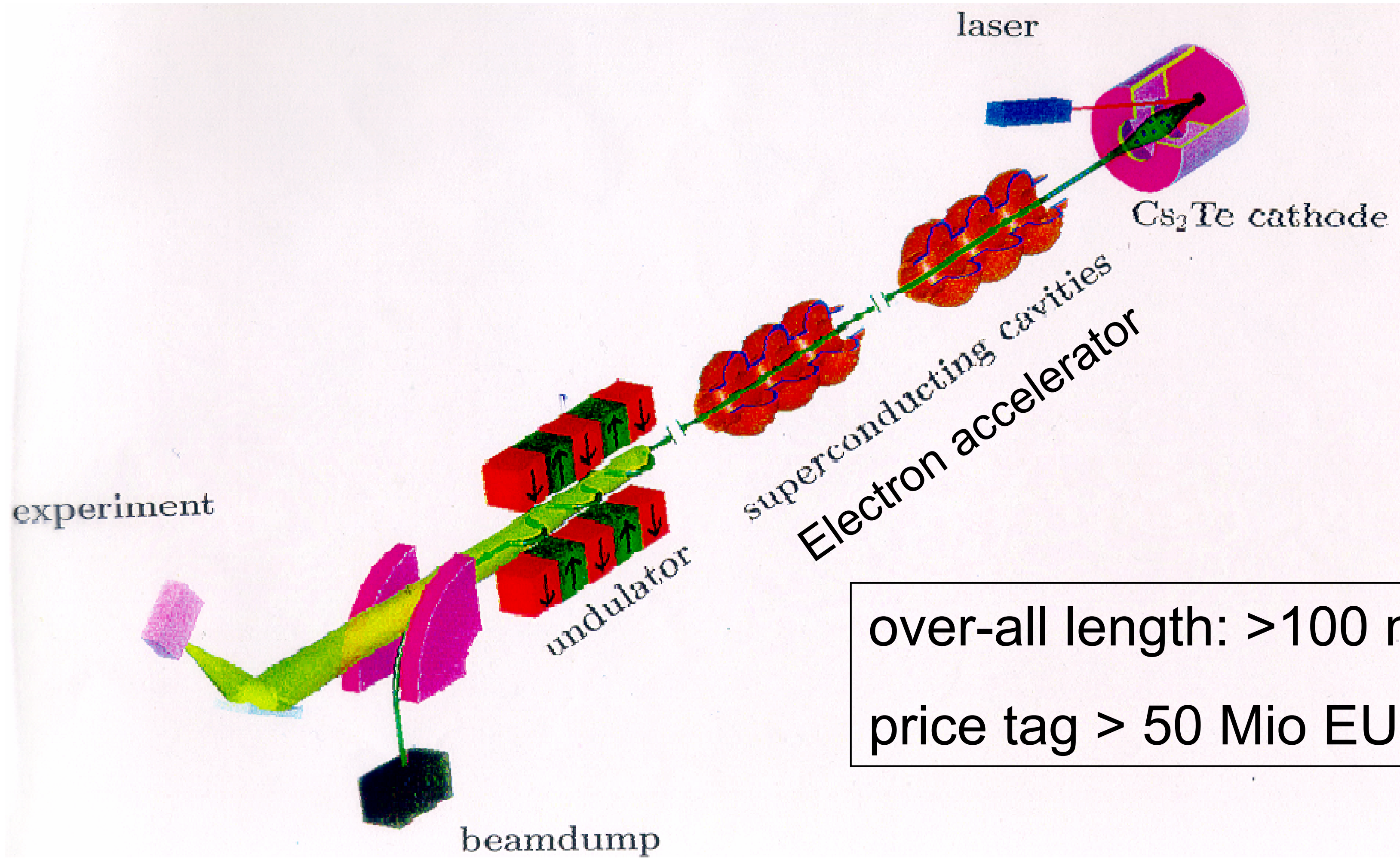
Magnetic Measurements Jan 08



12m Bench 22.1.08



Schematic of a high-gain Free-Electron Laser (FEL)



over-all length: >100 m

price tag > 50 Mio EUR

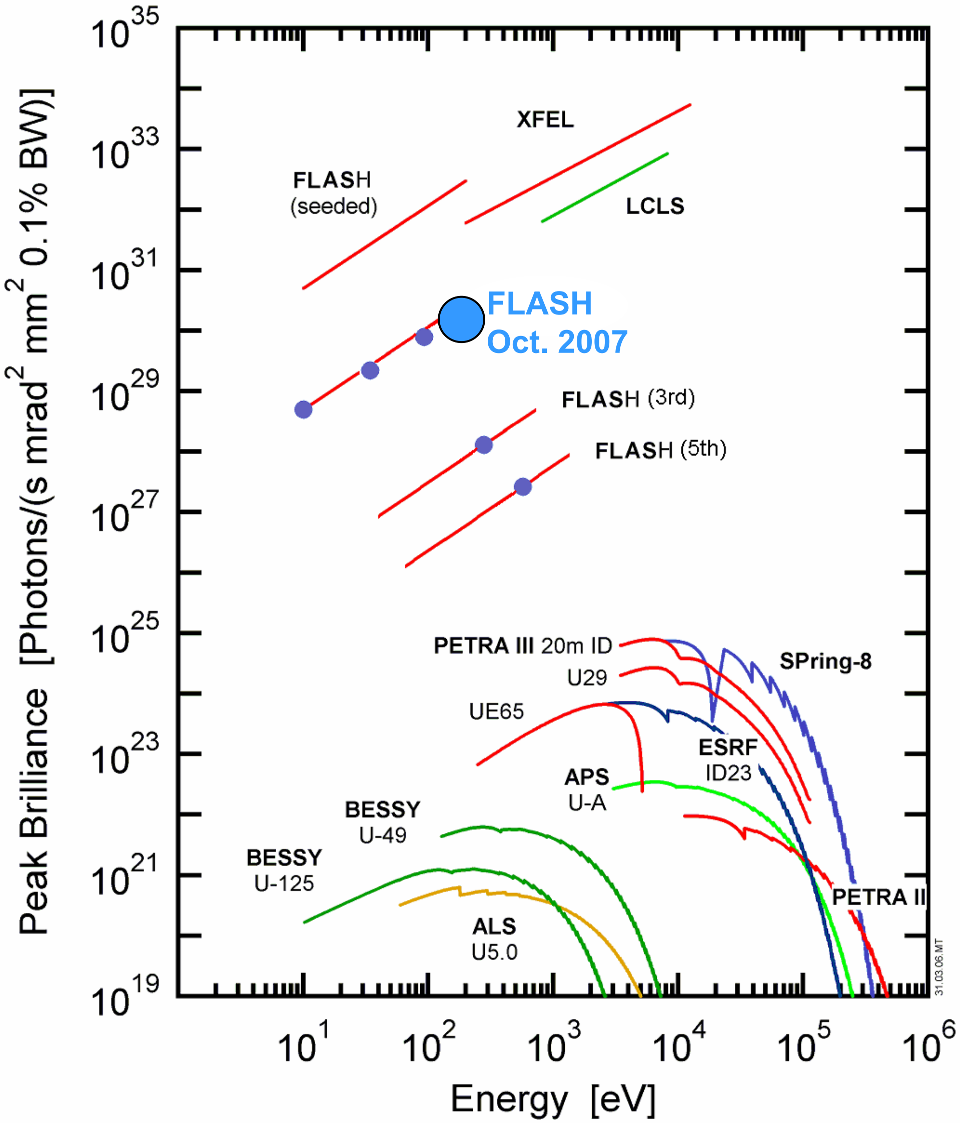
Why SASE FELs?

SASE = Self-Amplified Spontaneous Emission

Brilliance:

No. of photons

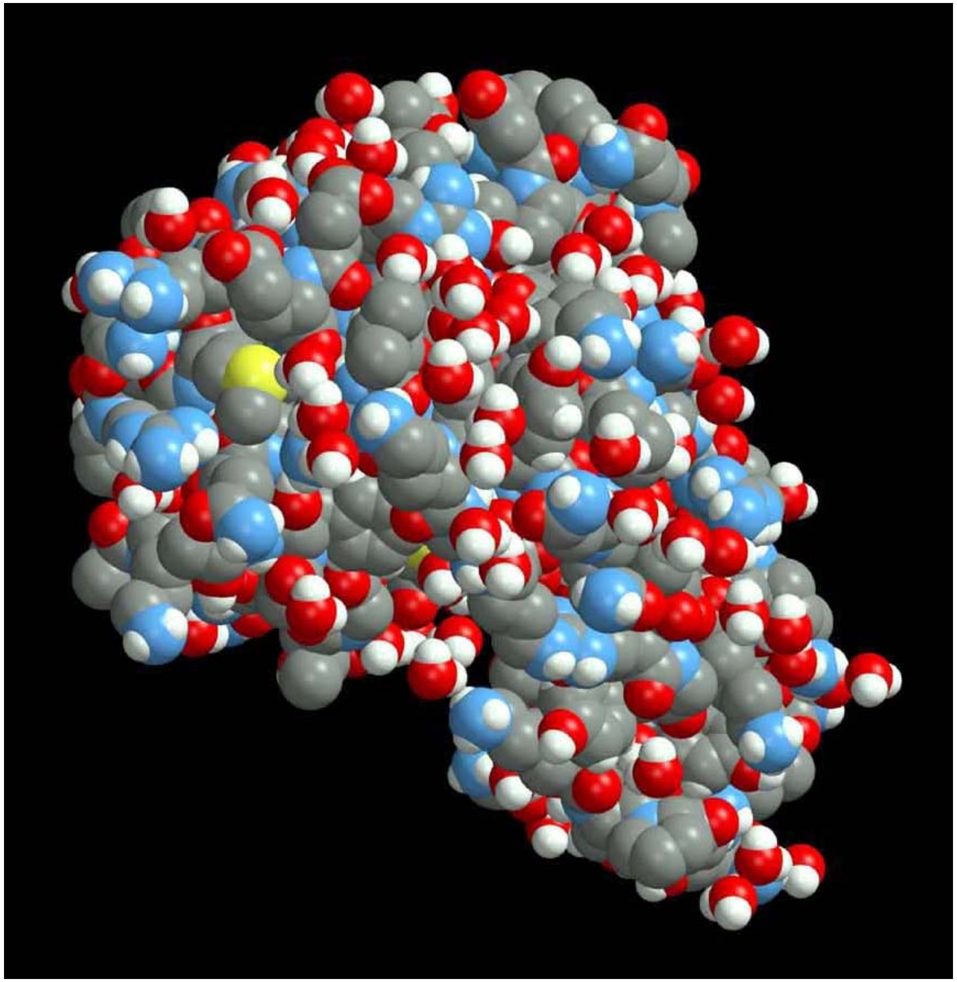
- per second
- per cross section of the radiating source
- per opening angle of radiation



This is the figure of merit for all experiments involving

- **diffraction**
- **very fast processes**

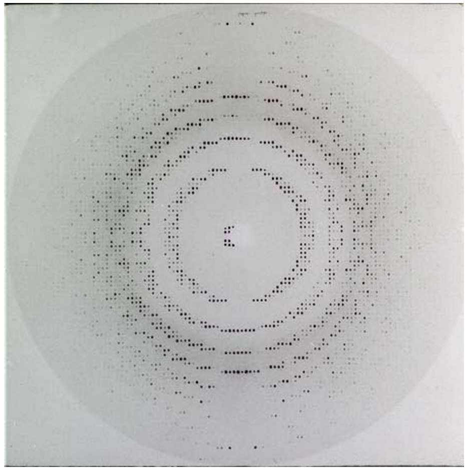
Why SASE FELs?



LYSOZYME , MW=19,806

State of the art:
Structure of biological macromolecule

reconstructed from diffraction pattern of protein crystal:



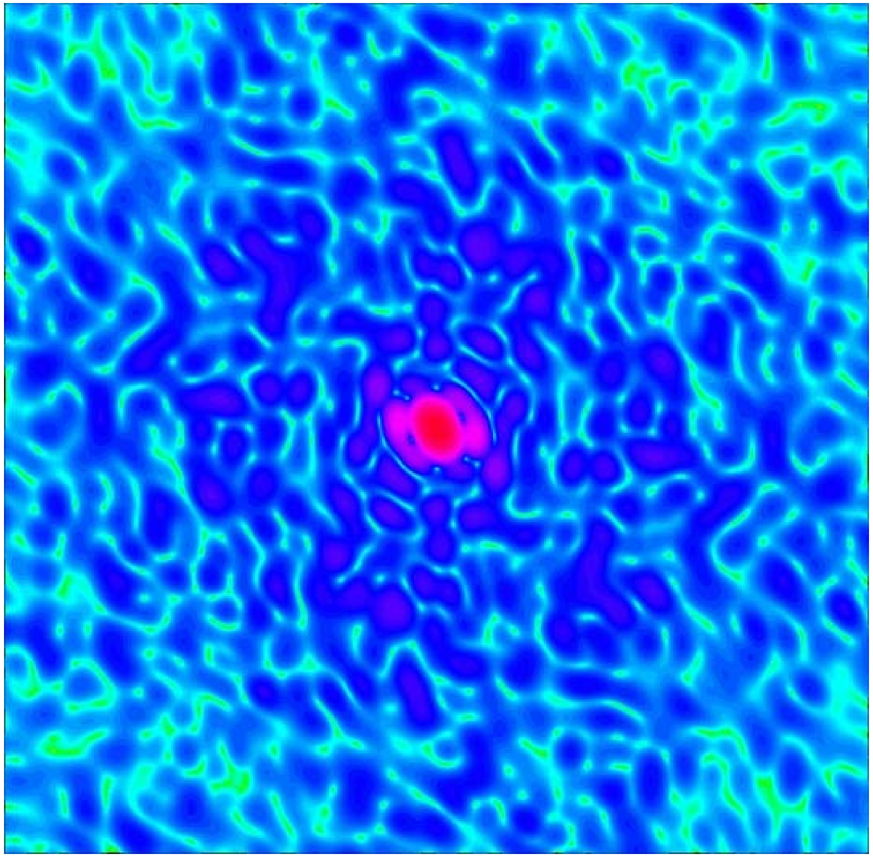
Needs ≈10^{15} samples

Crystallized → not in life environment

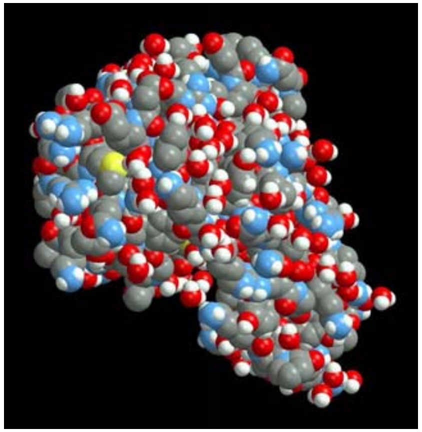
The crystal lattice imposes restrictions on molecular motion

Images courtesy Janos Hajdu

Why SASE FELs?



courtesy Janos Hajdu



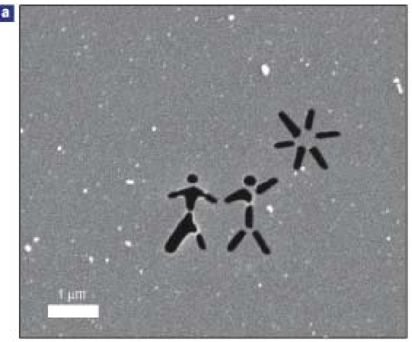
SINGLE MACROMOLECULE,
Planar section, simulated image

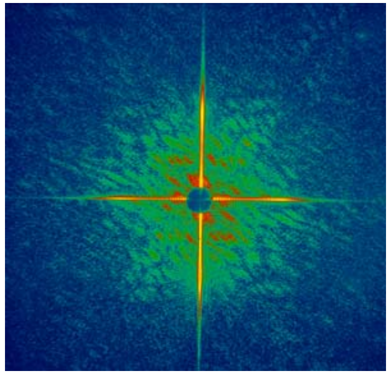
Resol. does not depend on sample quality

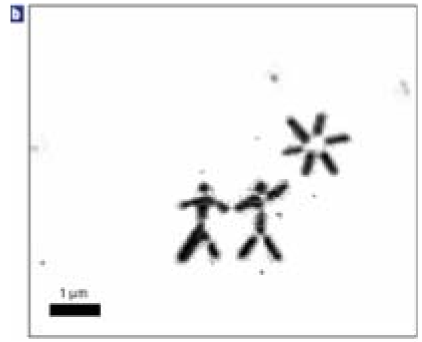
Needs very high radiation power @ $\lambda \approx 1$Å

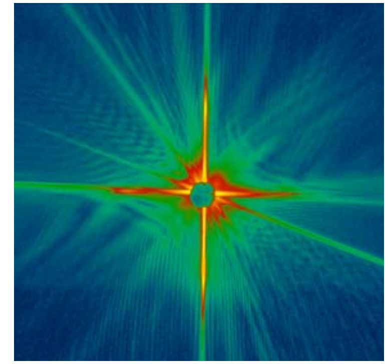
Can see dynamics if pulse length < 100 fs

Why SASE FELs?







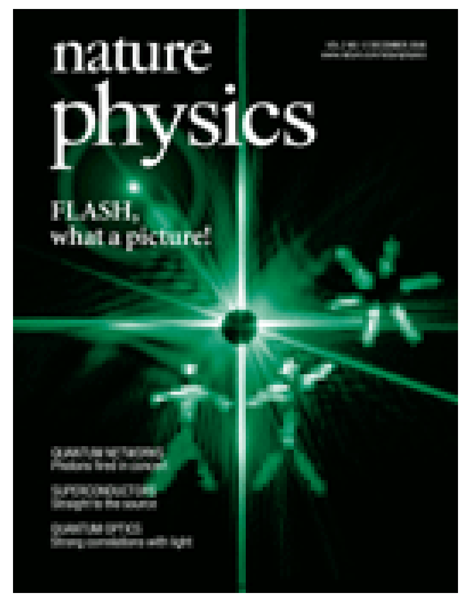


Object

Single pulse diffraction reveals structure before radiation damage occurs

Reconstructed from diffraction pattern

2nd pulse: object destroyed



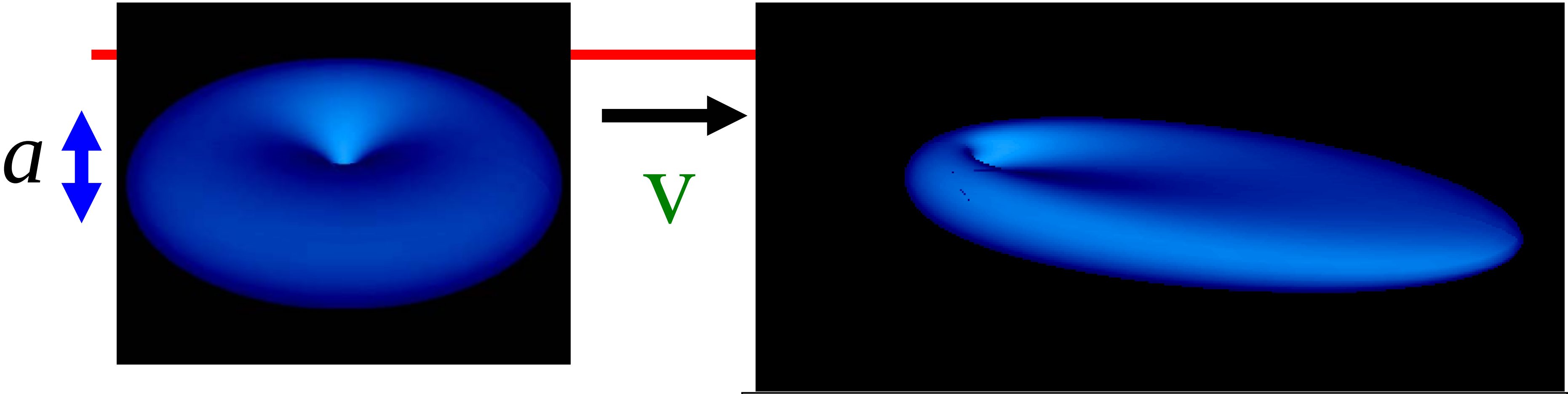
Why SASE FELs?

We need a radiation source with

- · very high peak and average power
- · wavelengths down to atomic scale $\lambda \sim 1$Å
- · spatially coherent
- · monochromatic
- · fast tunability in wavelength & timing
- · sub-picosecond pulse length

These are, typically, laser properties.
For wavelengths below ~100 nm: SASE FELs.

Basics: Radiation of a moving oscillating dipole



v = 0

local oscillator

$$\dot{v}_\perp = a\omega^2 \sin(\omega t)$$

$$P = \frac{Q^2 a^2}{4\pi\varepsilon_0 3c^3}\omega^4$$

$$(a < \lambda)$$

v = 0.9 c

moving oscillator

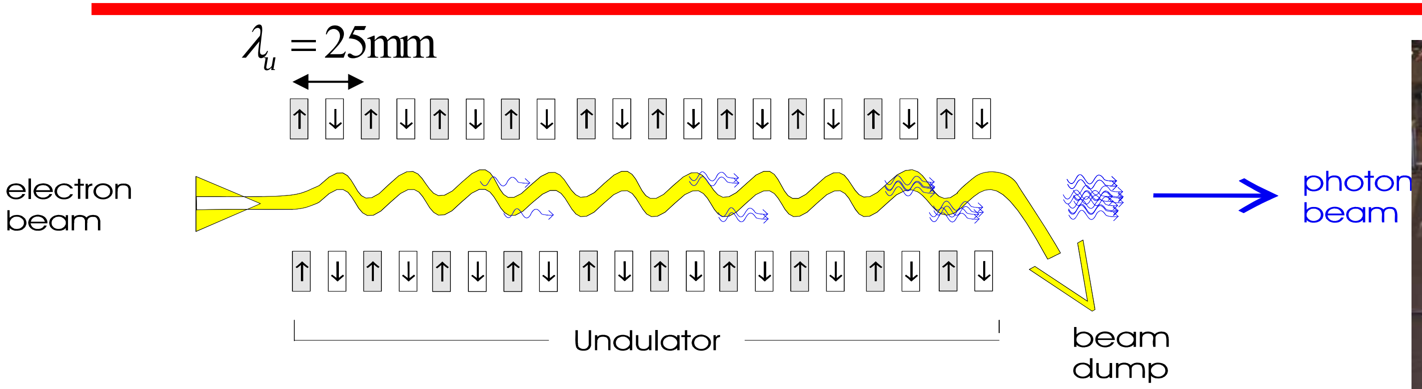
$$\gamma = \frac{E}{m_0 c^2}$$

$$P = \frac{Q^2 a^2}{4\pi\varepsilon_0 3c^3}\gamma^4\omega^4$$

We gain a factor of γ^4 in power!

note the quadratic dependence on charge!

Undulator Radiation



Radiation of an <u>ultrarelativistic</u> electron:

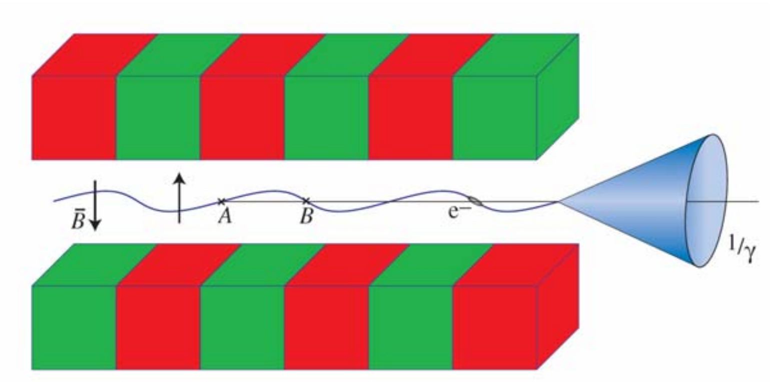
1) Moving coordinate system (*):

$$\lambda_u^* = \frac{\lambda_u}{\gamma} \quad \text{Lorentz length contraction} \rightarrow \text{electron oscillates with } \omega^* = 2\pi\frac{c}{\lambda_u^*} = \gamma \cdot \frac{2\pi c}{\lambda_u} = \gamma \cdot \omega$$

2) Lorentz transformation of radiation to lab-system (relativistic Doppler-effect):

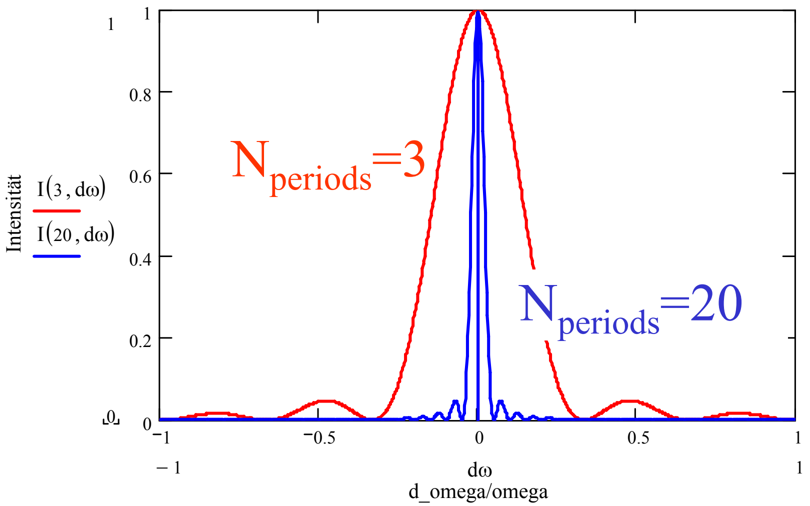
$$\lambda_{lab} = \frac{\lambda_u^*}{\gamma(1+\beta)} \approx \frac{\lambda_u}{2\gamma^2}$$

3) correction for $v_{long} \neq v$: $\boxed{\lambda_{lab} = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2/2\right)}$ $\quad K = \frac{e\lambda_u B}{2\pi m_0 c} \approx 1$: undulator parameter



Undulator radiation is emitted into narrow cone:

$$\text{Opening angle} \approx \frac{K}{\gamma}$$



Line width of $N_{periods}$:

$$\frac{d\omega}{\omega} \approx \frac{1}{N_{periods}}$$

www-xfel.spring8.or.jp

NOTE: $P = \dfrac{Q^2 a^2}{4\pi\varepsilon_0 3c^3}\gamma^4\omega^4$ assumes point-like charge Q!

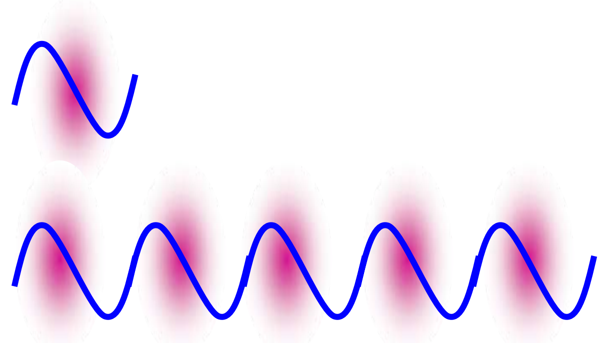
If Q consists of many particles, this requires that all charges are concentrated within distance λ !

→ FREE-ELECTRON LASER

→ desired: bunch length < wavelength

OR (even better)

Density modulation at desired wavelength



→ Potential gain in power: $N_e \sim 10^6$!!

FEL Basics

Idea:

Start with an electron bunch much longer than the desired wavelength
and find a mechanism that cuts the beam into equally spaced pieces automatically

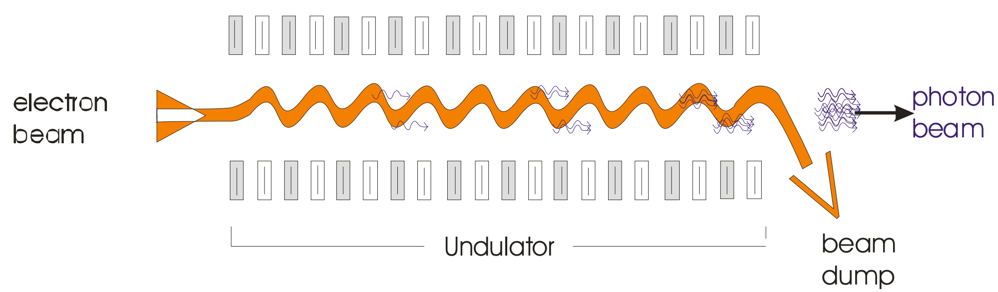
Free-Electron Laser

(Motz 1950, Phillips ~1960, Madey 1970)

Special version: starting from noise (no input needed)
Single pass saturation (no mirrors needed)

Self-Amplified Spontaneous Emission (SASE)

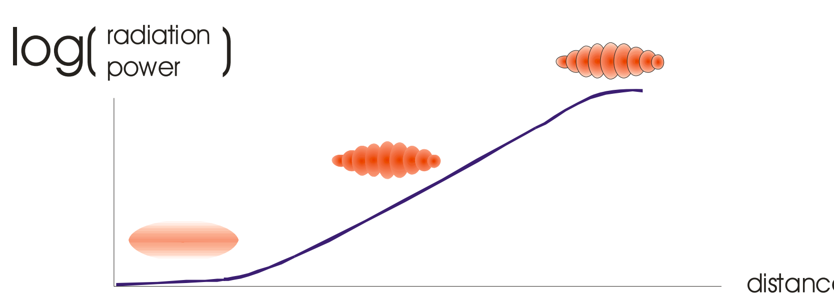
(Kondratenko, Saldin 1980)
(Bonifacio, Pellegrini 1984)



Resonance wavelength:

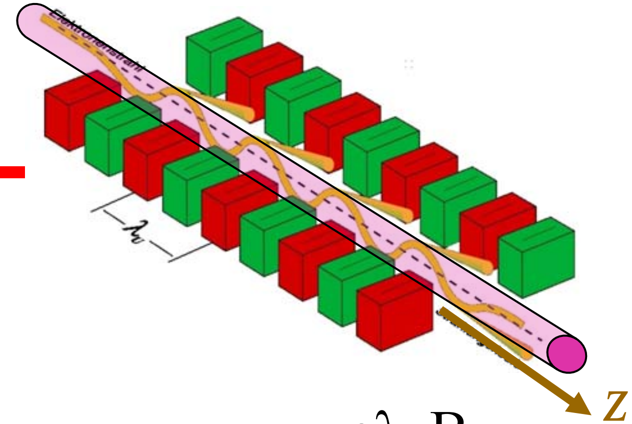
$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

Undulator parameter ≈ 1



Coherent motion is all we need !!

Basic theory of FELs



Step 1: Energy modulation

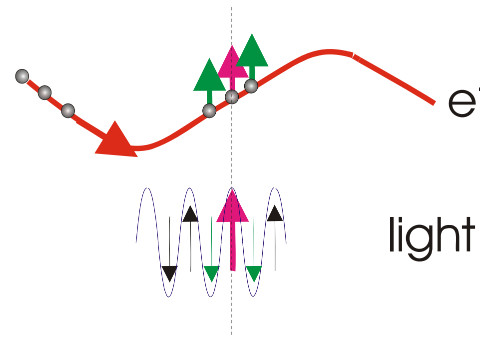
A: Electron travels on sine-like trajectory

$$\mathrm{v}_x(z) = c\frac{K}{\gamma}\cos\left(\frac{2\pi}{\lambda_u}z\right)$$, with undulator parameter: $$\mathrm{K} = \frac{\mathrm{e}\lambda_\mathrm{u}\mathrm{B}}{2\pi \mathrm{m_e c}}$$

B: External electromagnetic wave moving parallel to electron beam:

$$E_x(z,t) = E_0\cos(k_L z - \omega_L t)$$

Change of energy W in presence of electric field:



$$\frac{dW}{dz} = \frac{q}{\mathrm{v_z}}\vec{\mathrm{v}}\vec{E} = -\frac{qE_0K}{\gamma\beta_z}\sin\Psi,$$

with the ponderomotive phase: $\boxed{\Psi = (k_u + k_L)z - \omega_L t + \varphi_0}$

Note: $\cos\alpha\cdot\cos\beta = \frac{1}{2}\cos(\alpha+\beta) + \cancel{\frac{1}{2}\cos(\alpha-\beta)} = \frac{1}{2}\sin(\alpha+\beta+\pi/2)$

Basic FEL theory

$$\boxed{\frac{dW}{dz} = -\frac{qE_0 K}{\gamma\beta_z}\sin\Psi}$$

$$\Psi = \left(k_u + k_L\right) z - \omega_L t + \varphi_0$$

The energy *dW* is taken from or transferred to the radiation field.
For most frequencies, *dW/dz* oscillates very rapidly.

Continuous energy transfer ?

Yes, if Ψ constant.

$$\rightarrow \quad \frac{d\Psi}{dz} = 0\ ! \quad \rightarrow \quad \mathrm{k_u} + k_L - \frac{k_L}{\beta_z} = 0$$

→ Resonance condition: $\lambda_\mathrm{L} = \dfrac{\lambda_\mathrm{u}}{2\gamma^2}\left(1 + \dfrac{\mathrm{K}^2}{2}\right)$

Note: Same equation as for wavelength of undulator radiation.

→ Energy modulation inside electron bunch <u>at optical wavelength !</u>

Basic FEL theory

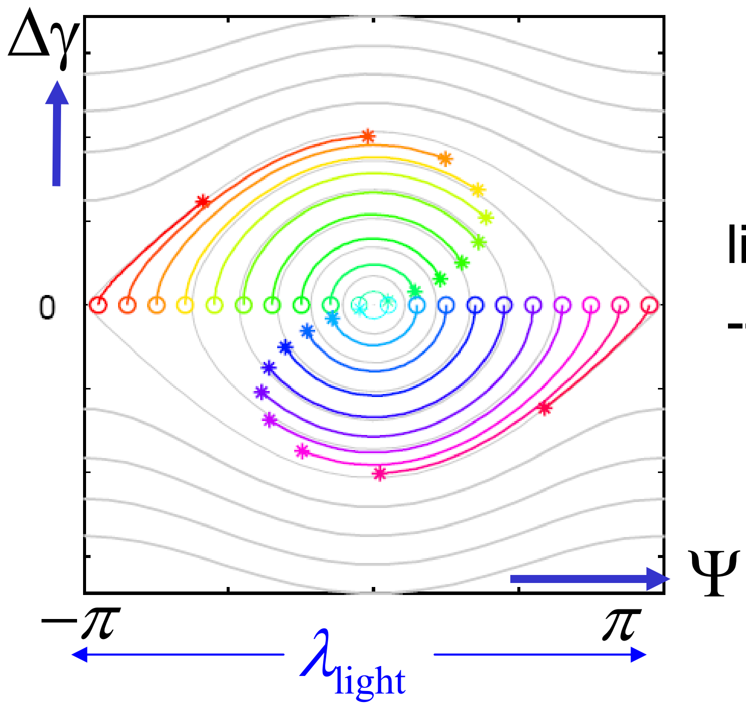
Step 2: Current modulation

Energy modulation by $\Delta\gamma$ leads to change of Phase Ψ:

$$\boxed{\frac{d\Psi}{dz} = k_u \frac{2}{\gamma_{res}} \Delta\gamma}$$

Combination with Step 1: $\frac{dW}{dz} = -\frac{qE_0 K}{\gamma\beta_z}\sin\Psi$ yields

$$\boxed{\frac{d^2\Psi}{dz^2} = -\Omega^2 \sin\Psi \quad \text{with} \quad \Omega^2 = \frac{q}{m_0 c^2}\frac{\mathbf{E}_0 K k_u}{\gamma_{res}^2 \beta_z}}$$



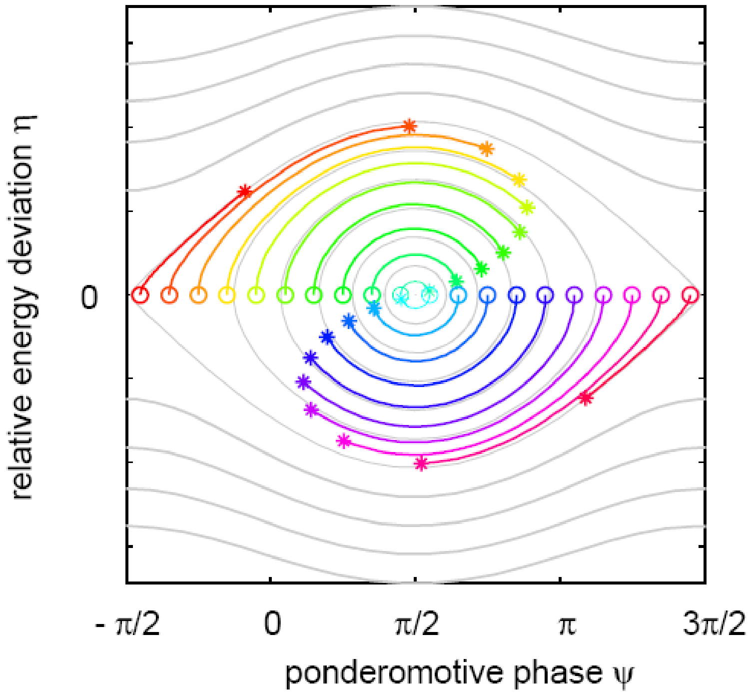
like synchrotron oscillation

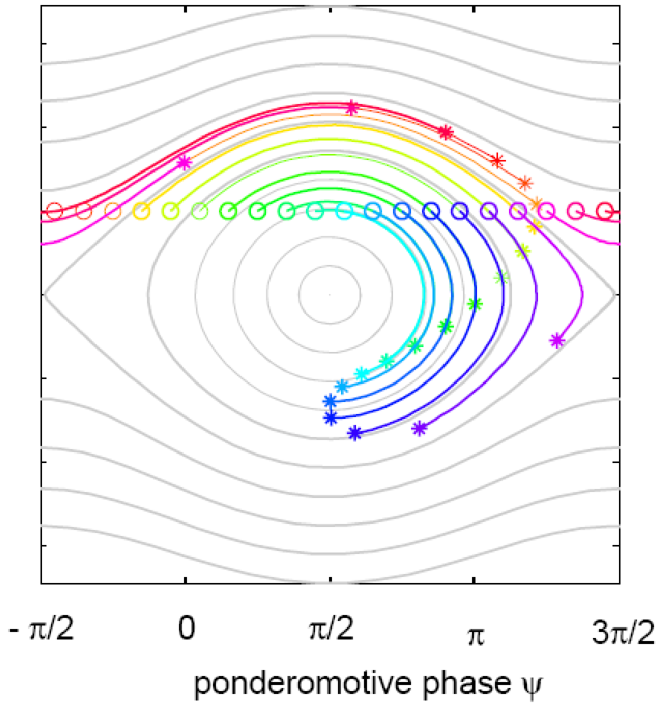
-- but at spatial period λ_{light}

Phase space simulation of low gain FEL slightly above resonance → See electron bunch losing energy in average

→ current modulation !!

Gain (or loss) in field energy per undulator passage, depending on where to start in phase space :





Phase space simulation of low gain FEL slightly above resonance →
See electron bunch losing energy in average

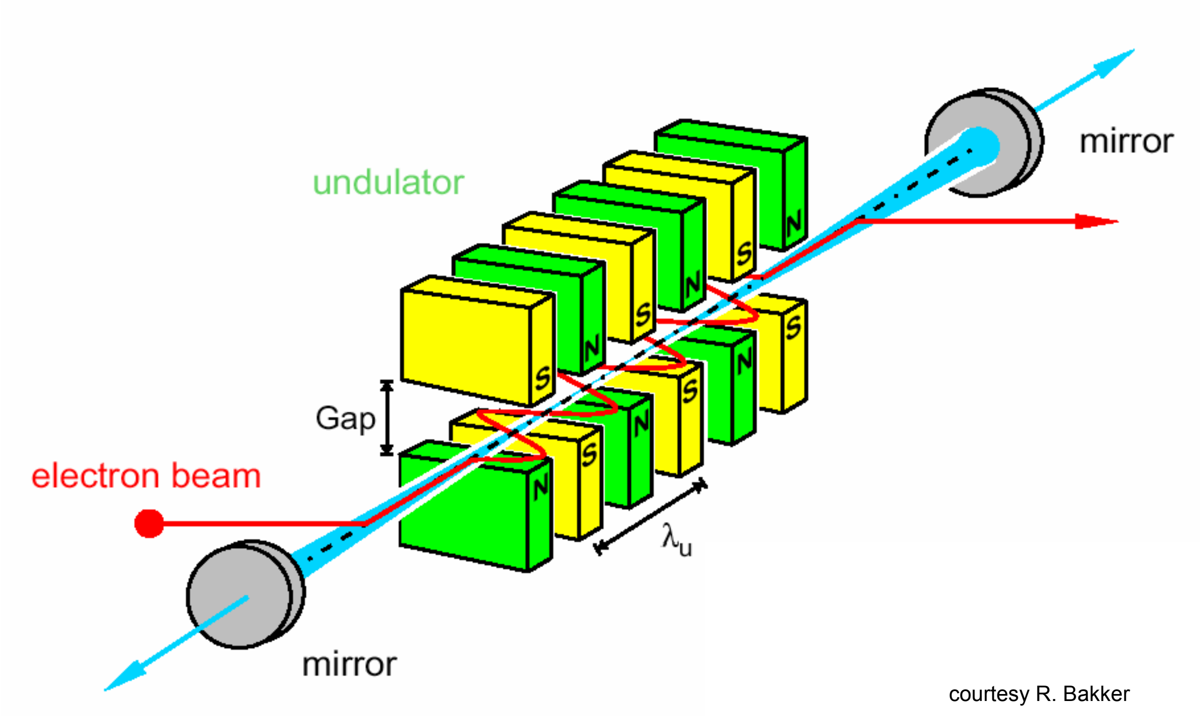
$$G_i = \frac{\text{gain of field energy produced by electron } i}{\text{total field energy}} \rightarrow \text{ requires solution of pendulum equation for } \gamma(z).$$

Real beam may have well defined energy, but all phases are equally probable!

→ Need to average gain for fixed energy Δγ over all phases

The “low gain” FEL

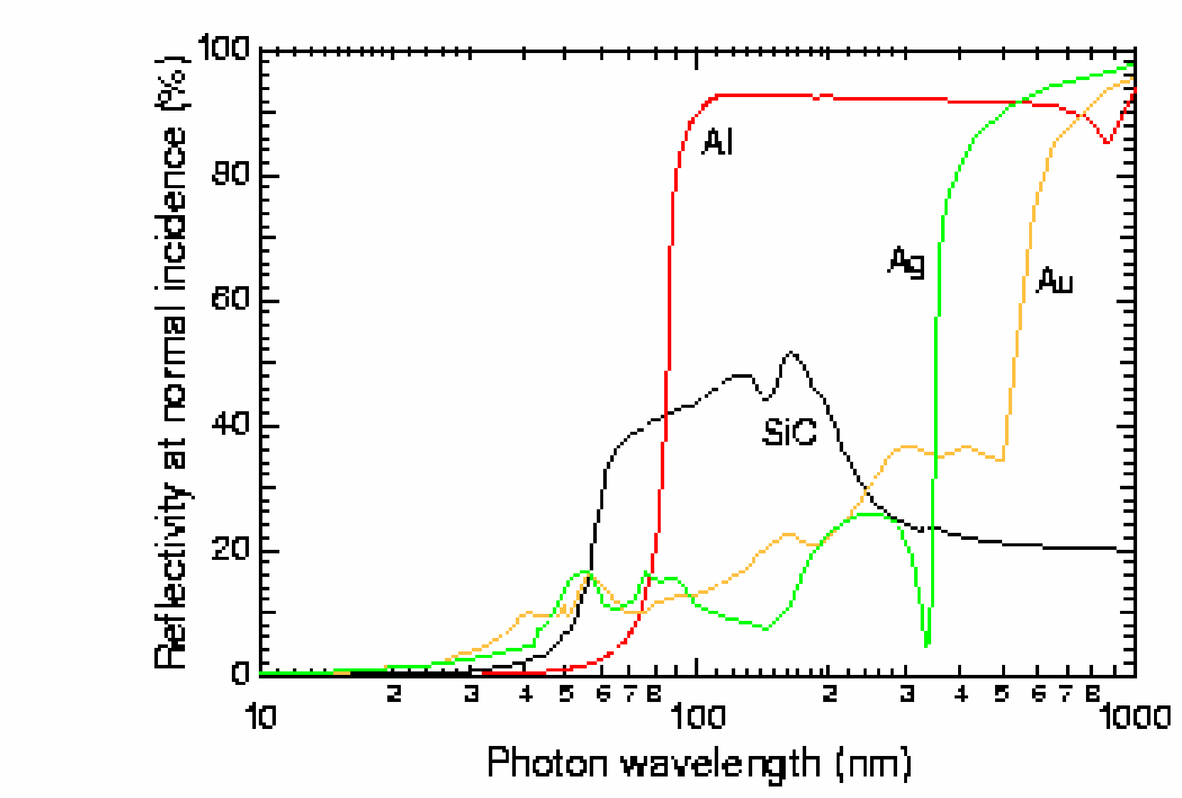
For many FELs, it is sufficient to have only a few % power gain (low gain FEL). Using a pair of mirrors, one can multiply the gain, if on each round trip of radiation there is a fresh electron bunch available.
After N round trips, $G_{total} = G^N$, which can be a very big number.



courtesy R. Bakker

Only few % of radiation intensity is extracted per electron passage (mirror reflectivity) to keep stored field high

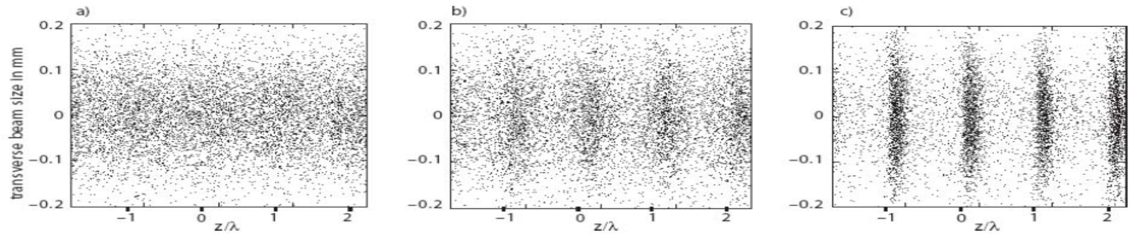
Very nice scheme.
But what if we want wavelength < approx. 100nm where no good mirrors exist?



Reflectivity of most surfaces at normal incidence drops drastically at wavelengths below 100 – 200 nm.

High gain FEL =

we take into account that the initial, external e.m. field changes during FEL process



Step 3: Radiation

Current modulation j_{Light} drives radiation of light:

$$\frac{\partial^2 E_\perp}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E_\perp}{\partial t^2} = \mu_0 \frac{\partial j_\perp}{\partial t}$$

Approximation: field growth slow compared to $1/\omega_{Light}$

$$\boxed{\frac{dE_{Light}}{dz} \approx \text{const} \cdot j_{modulation}}$$

System of Diff. Eqs. defines **High Gain FEL:**

(To be solved numerically for given distribution of electrons)

$$\frac{d}{dz}\begin{pmatrix} \Delta\gamma \\ \psi \\ E_{Light} \end{pmatrix} = \begin{pmatrix} -\frac{qE_{Light}K}{m_e c^2 \gamma_{res}^2} \sin\Psi \\ k_u \frac{2}{\gamma_{res}} \Delta\gamma \\ \text{const} \cdot j_{modulation} \end{pmatrix}$$

Energy modulation

Density modulation

Radiation

Analytical Theory of High-gain FEL

Ansatz: $\mathrm{j(z)} = \mathrm{j}_0 + j_1(z)\cos(\Psi + \psi_0)$

i.e. we assume a density modulation at the optical wavelength

Maxwell Eq. combined with Vlasov Eq. results in a linear integro-differential equation for the (complex) electric field amplitude **E(z)** growing with z.

Most simple case: All electrons on resonance energy →

$$\boxed{\frac{\mathrm{d}^3 \mathbf{E}}{dz^3} = i\Gamma^3 \mathbf{E}} \quad . \quad \text{Ansatz:} \quad \mathbf{E} = A\,\mathbf{exp(}\Lambda z\mathbf{)} \quad \rightarrow \quad \Lambda^3 = i\Gamma^3$$

$$\Rightarrow \Lambda_1 = -i\Gamma; \quad \Lambda_2 = \frac{i+\sqrt{3}}{2}\Gamma; \quad \Lambda_3 = \frac{i-\sqrt{3}}{2}\Gamma$$

Abbreviation:

Gain Factor: $\Gamma = \left(\dfrac{\pi j_0 K^2 (1+K^2)\omega_L}{I_A c \gamma^5} \right)^{1/3}$

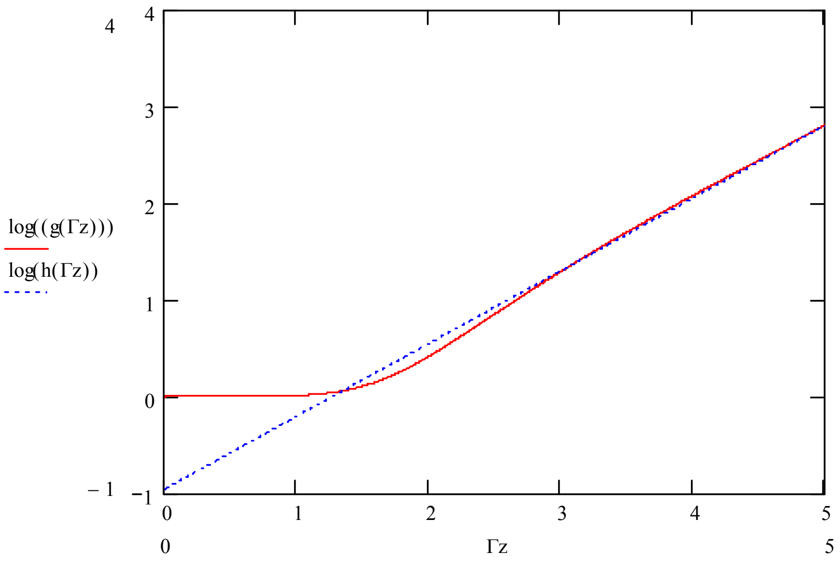
Alven current: $\mathrm{I_A} = 17\ \mathrm{kA}$

The power gain is given by (prove it!)

$$G = \frac{\left|\tilde{\mathbf{E}}\right|^2}{\mathbf{E}_{\text{ext}}^2} = \frac{1}{9}\left[1 + 4\cosh\frac{\sqrt{3}}{2}\Gamma z\left(\cosh\frac{\sqrt{3}}{2}\Gamma z + \cos\frac{3}{2}\Gamma z\right)\right]$$

$\rightarrow$ (for z>>1/Γ): $\boxed{G = \frac{1}{9}\exp\sqrt{3}\Gamma z}$

The factor 1/9 describes the coupling of the incoming e.m. field to FEL gain process



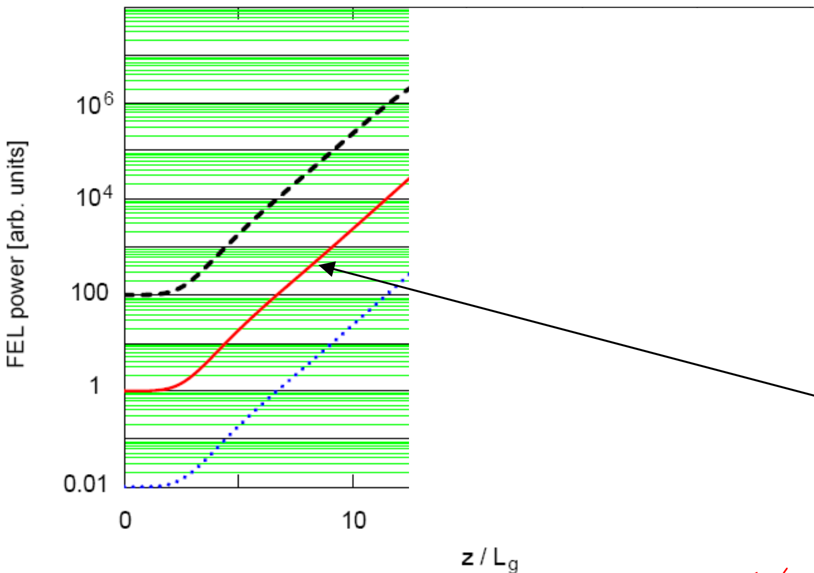
Bunching at SASE FEL seen in y/z coordinates

$$P_{rad} = \frac{1}{9} P_{in} \exp\left(\sqrt{3}\Gamma z\right) = \frac{1}{9} P_{in} \exp\left(z/L_G\right) \quad .$$

$$L_G = \frac{1}{\sqrt{3}}\left(\frac{I_A c\gamma^5}{\pi j_0 K^2 (1+K^2)\omega_L}\right)^{1/3} \quad \text{or, using} \quad \omega_{\mathrm{L}} = \frac{4\pi c\gamma^2}{\lambda_u (1+K^2)} \quad \text{and } j_0 \approx \frac{\hat{I}}{\pi\sigma_{\mathrm{r}}^2} \; ,$$

$$L_{\mathrm{G}} = \frac{1}{\sqrt{3}}\left(\frac{I_A \gamma^3 \sigma_{\mathrm{r}}^2 \lambda_u}{4\pi \hat{I} K^2}\right)^{1/3} \quad \text{is called power gain length.}$$

Theory: High-gain FEL



Evolution of radiation power:

$$P_{rad} \propto |\mathbf{E}(z)|^2 \quad \text{with} \quad \mathbf{E}(z) = \frac{1}{3} E_{in} \exp\left(\frac{i + \sqrt{3}}{2} \Gamma z \right)$$

$z >> \Gamma^{-1}$: exponential growth:

$$\boxed{P_{rad} = \frac{1}{9} P_{in} \exp\left(\frac{z}{L_G} \right)} \qquad L_G = \frac{1}{\sqrt{3}} \left(\frac{I_A \gamma^3 \sigma_r^2 \lambda_u}{4\pi \cdot \hat{I} \cdot K^2} \right)^{1/3}$$

$$L_G \propto (\text{current density})^{-1/3} \qquad \rho_{FEL} = \frac{1}{4\pi\sqrt{3}} \frac{\lambda_u}{L_G} \approx 10^{-4} \ldots 10^{-2}$$

1. Expect exponential gain with e-folding length L_G
   Major additional assumption: Orbit is perfectly straight

2. Gain should saturate when modulation is complete

P_{in} = input power;
may also be spontaneous radiation from first part of the undulator.

Exponential growth of power at SASE FEL

→Self-Amplified Spontaneous Emission (SASE) mode of operation
→ Most attractive for (short) wavelengths where no mirrors and no good (= powerful and tunable) input laser are available.

Present world record w.r.t. short wavelengths (6.5 nm):
Power gain $P_{rad}/P_{in} = 10^6$ demonstrated at DESY

Saturation takes place after $L_{sat} = \dfrac{\lambda_u}{\rho} \approx 22 L_G$.

Peak power 1 GW

At saturation, the radiation band width is $\dfrac{\Delta\lambda_{rad}}{\lambda_{rad}} \approx \rho$,

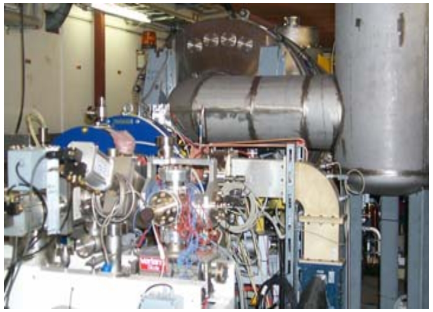
and the fraction of beam energy into (coherent!) radiation energy is also $\dfrac{E_{rad}}{E_0} \approx \rho$

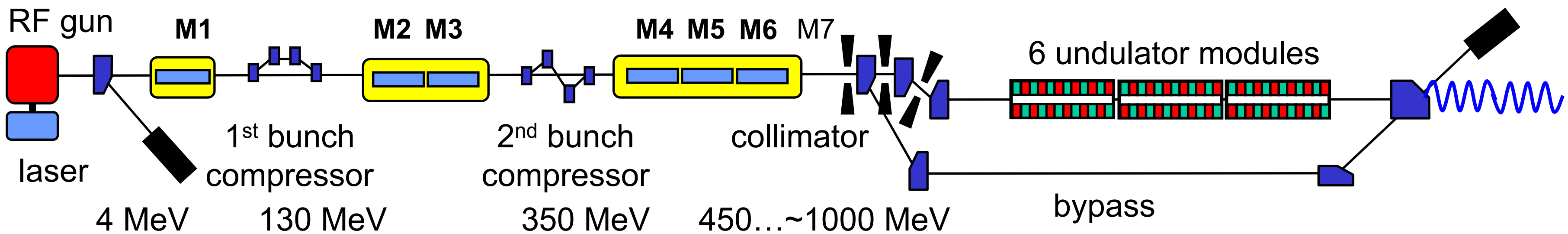
Why is such a device called a laser?

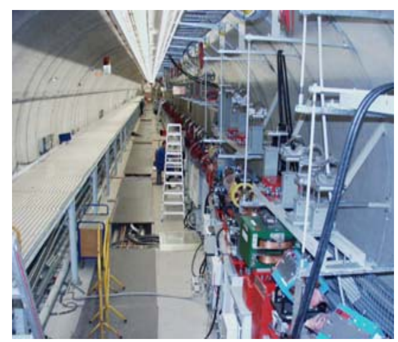
1. Emission of photons is stimulated by the presence of the electromagnetic field inside the undulator
   - electron beam takes the role of active medium
2. Radiation properties are typical for lasers

What do we observe ?

Present set-up of the FLASH accelerator

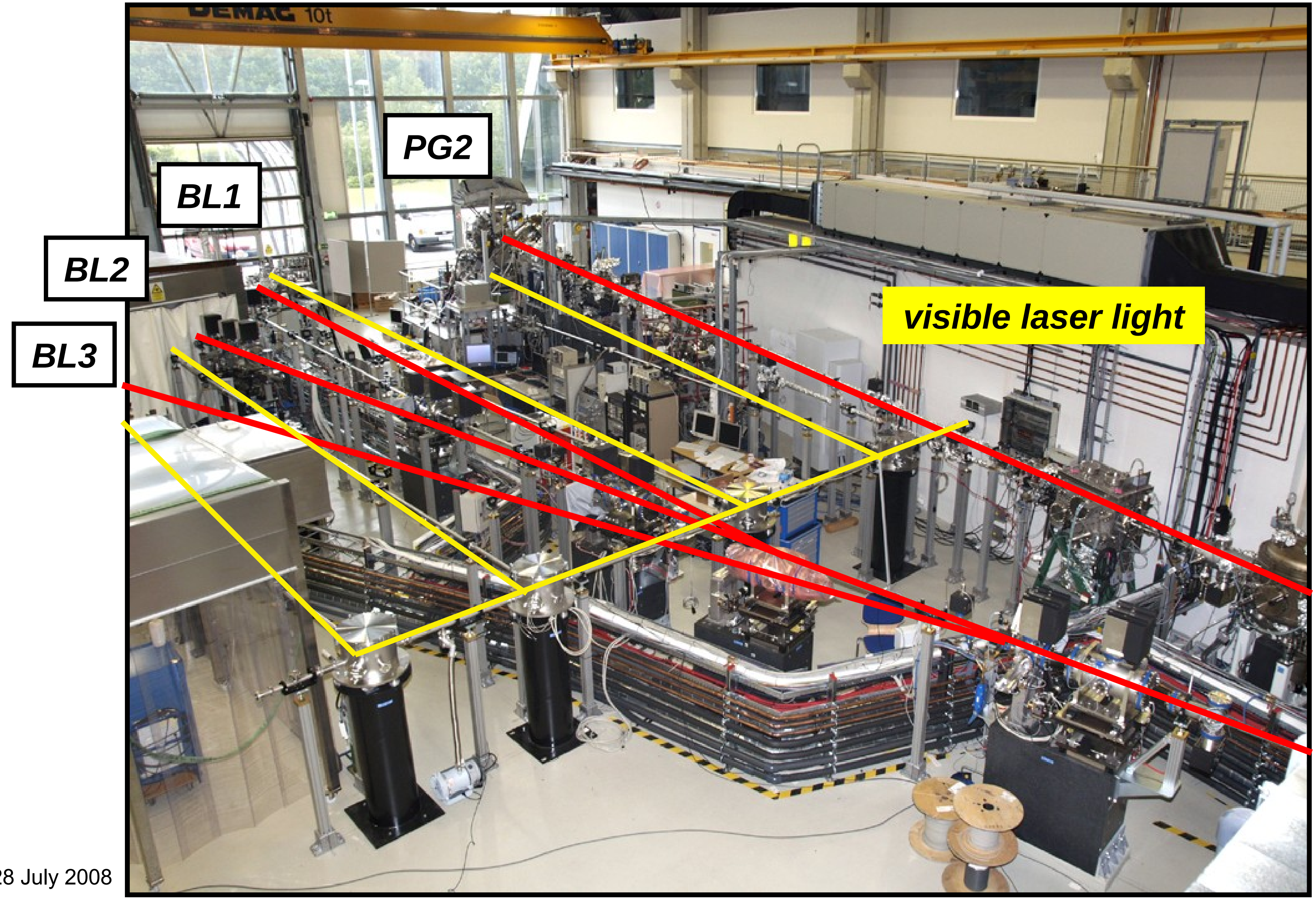






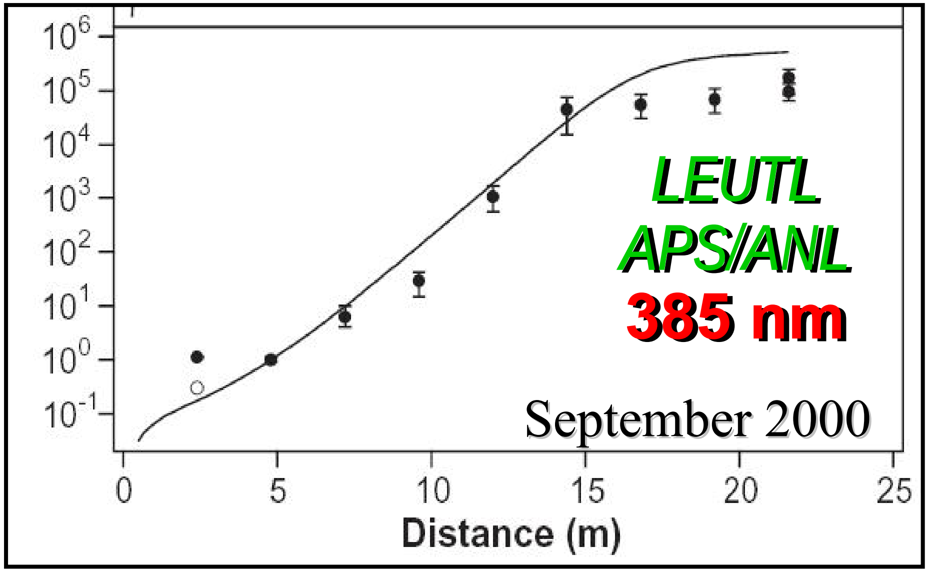
250 m

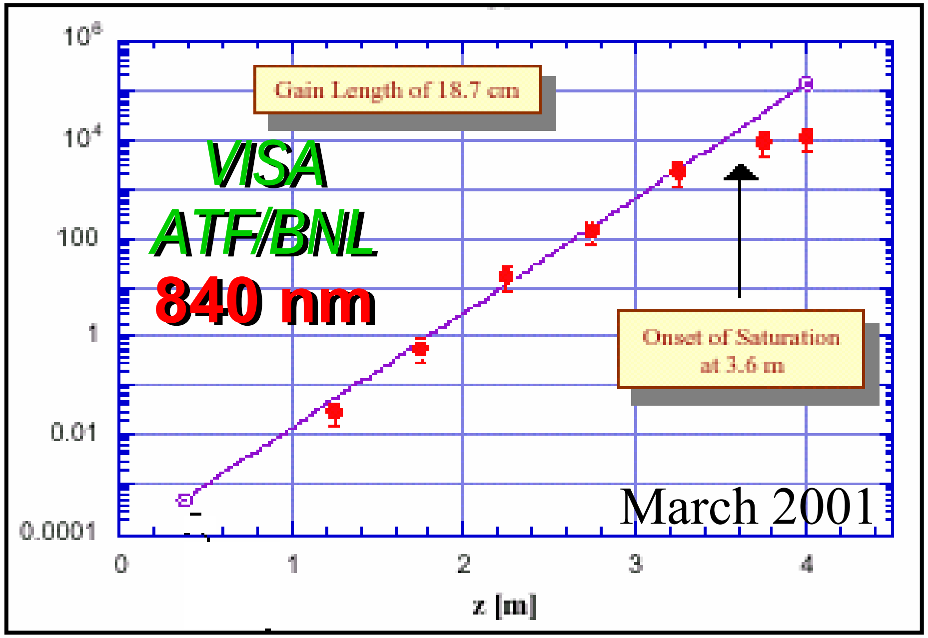
FLASH: the VUV-FEL User Facility at DESY

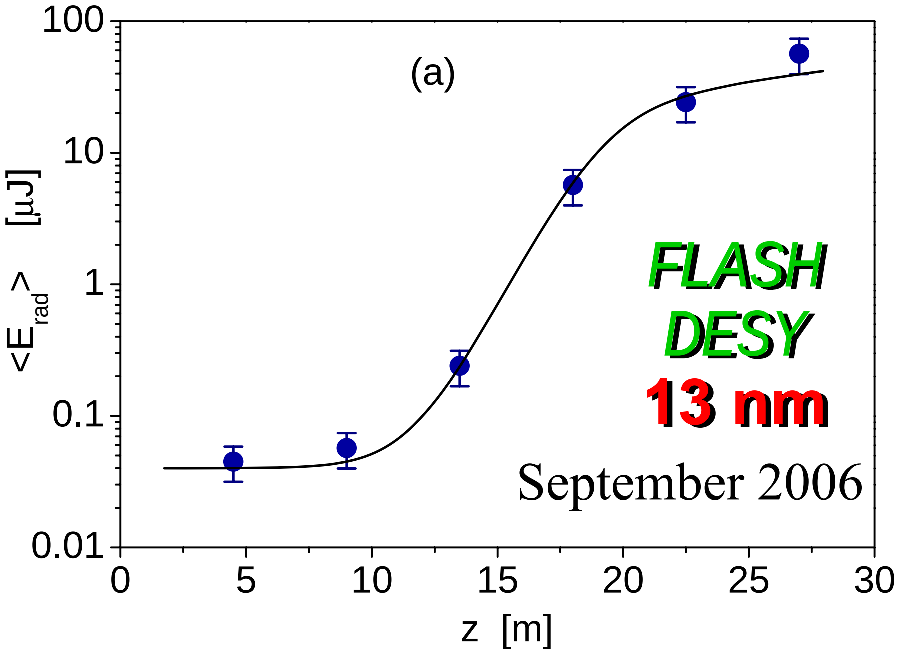


High-Gain FELs:
State of the art

All observations agree with theor. expectations/ computer models

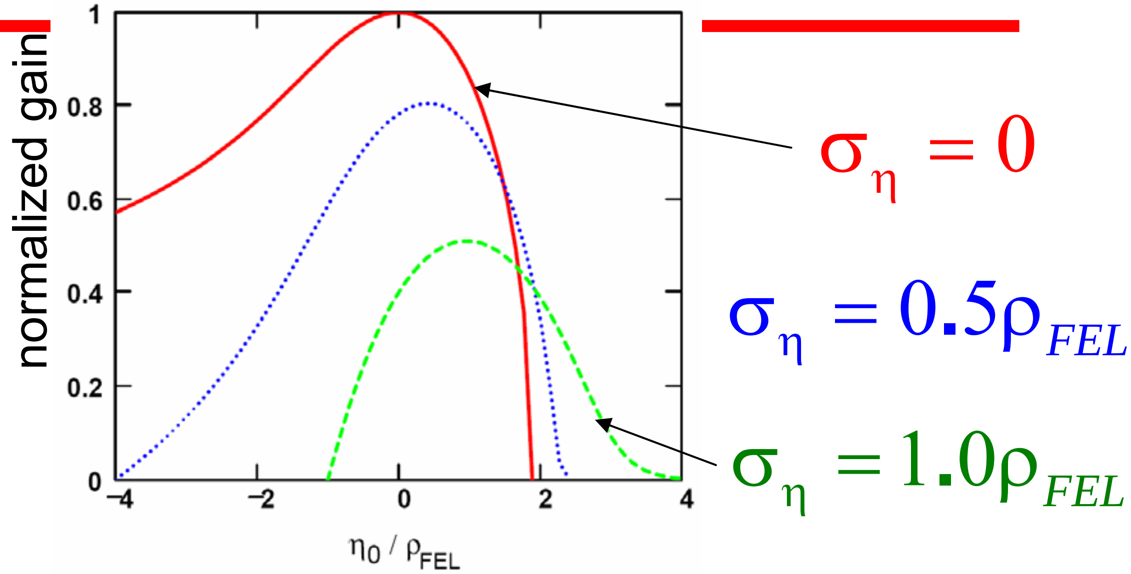






Bandwidth

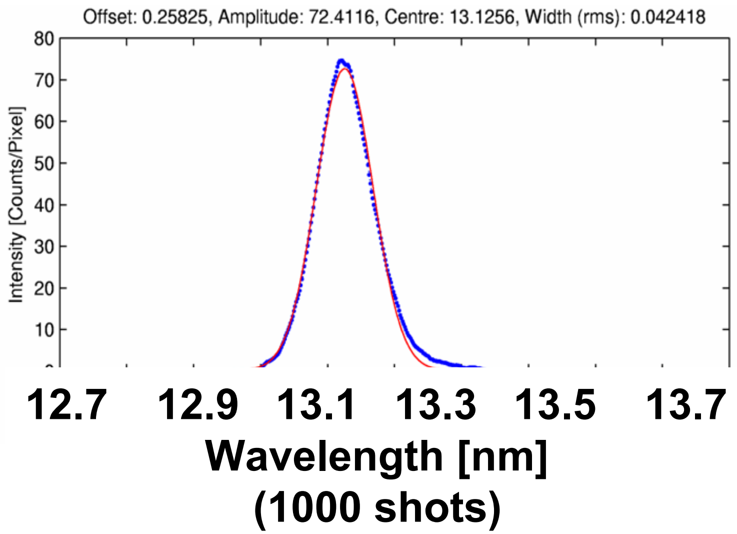
Gain drops vs. momentum error η=dp/p: (momentum spread σ_η)



FEL is a narrow band amplifier !

FLASH experiment:

Bandwidth agrees with theory



Transverse Coherence

Emittance of a perfectly coherent ("gaussian") light beam:

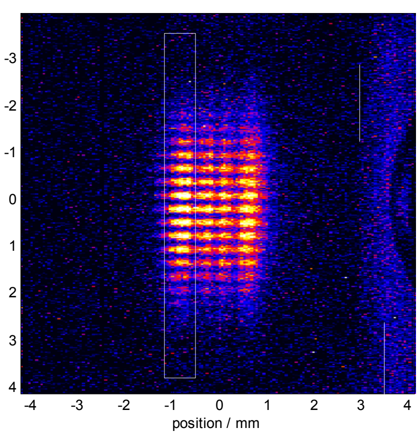
$$\varepsilon_{Light} = \sigma_r \cdot \sigma_\theta = \frac{\lambda_{Light}}{4\pi}$$

→ FEL theory predicts high transverse coherence of photon beam, if electron beam emittance:

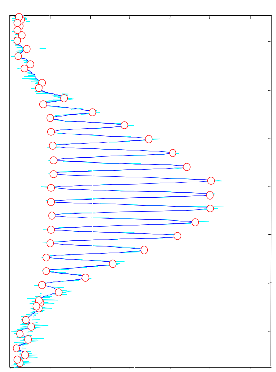
$$\boxed{\varepsilon_{electrons} < \approx \frac{\lambda_{Light}}{4\pi}}$$

Observation of interference pattern at FLASH:

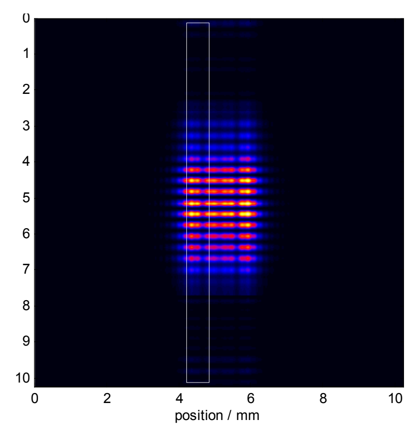
double slit



intensity modulation



FEL simulation



SASE FEL challenges

Most electron beam parameters relevant within slices < coherence length ~1 … 10 fs

- relaxes requirements on beam specs
- complicates measurements and beam dynamics

Emittance:	$\varepsilon \leq \lambda/4\pi \Leftrightarrow \sigma_r \approx 50\ \mu m$
Short Pulse length	$\sigma_s = 10 - 100$ fs
Peak current inside bunch:	$\hat{I} > 1$ kA
Energy width:	$\sigma_E/E \leq\sim 10\text{-}3$
Straight trajectory in undulator	$< 10\ \mu m$

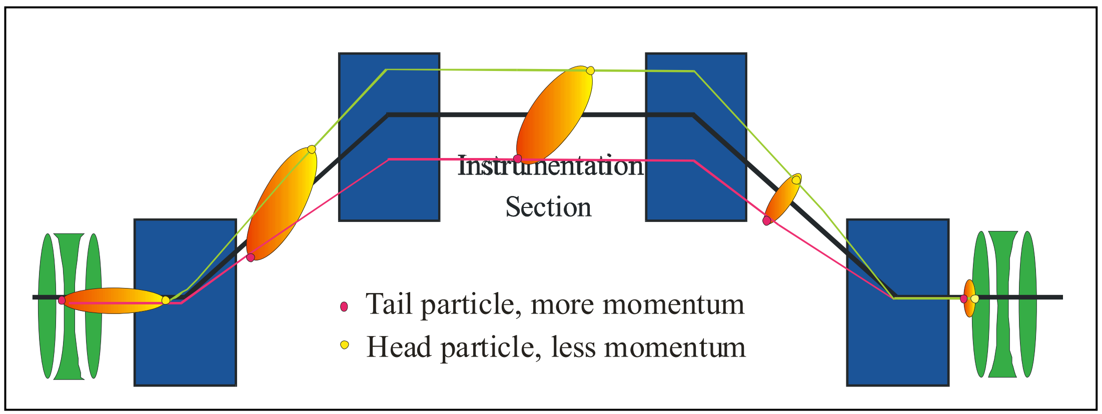
Increasingly difficult for shorter wavelength:

longer undulator, smaller emittance, larger peak current

Longitudinal Bunch C

Need large peak current (> 1kA) ins

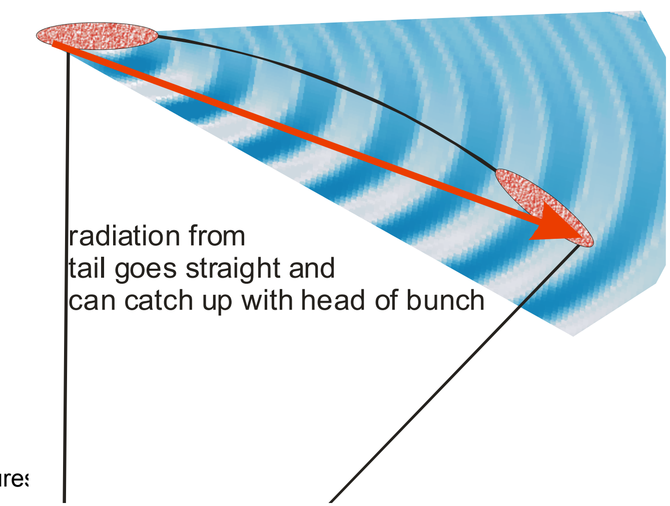
→ must compress bunches l



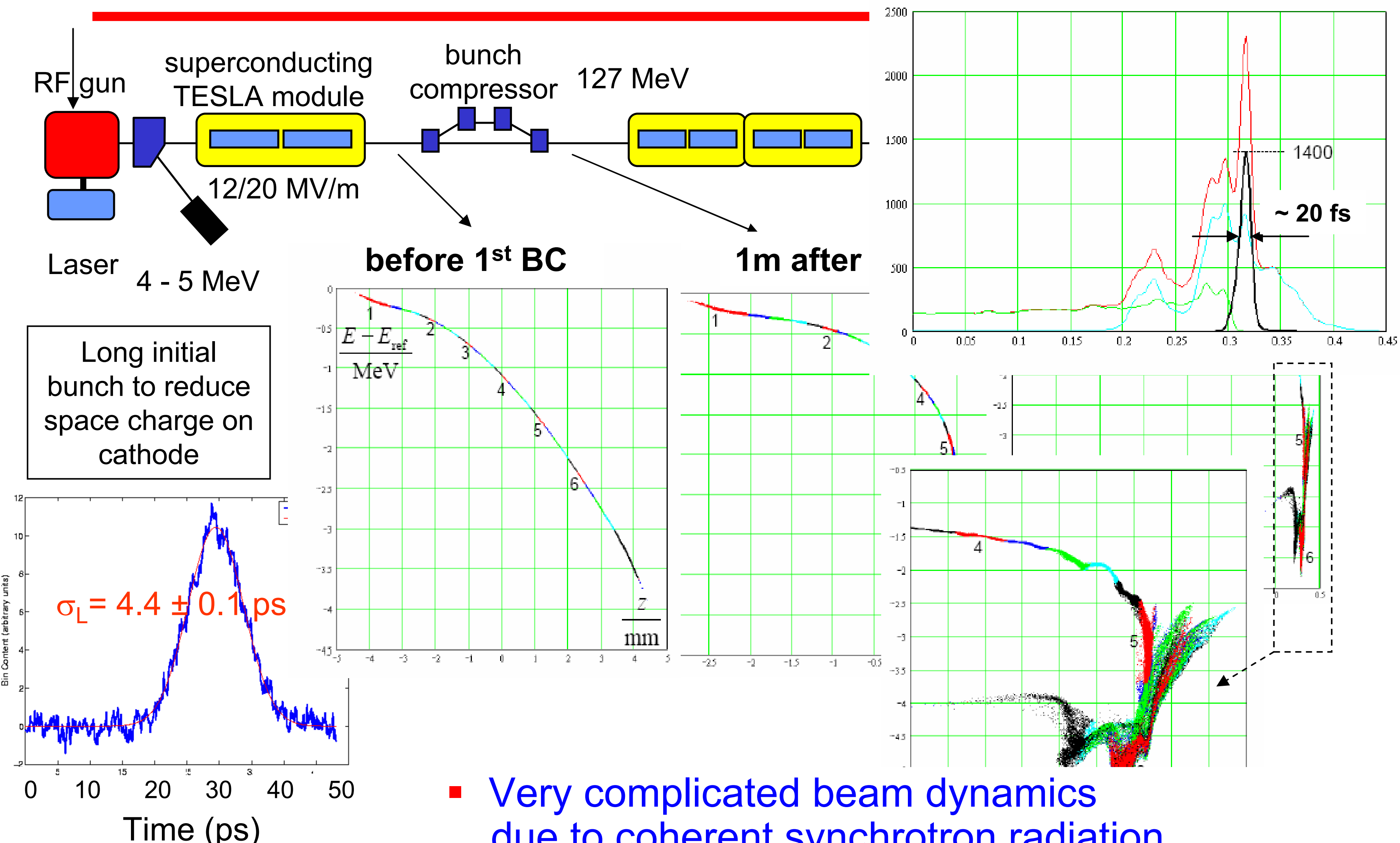
Magnetic bunch compression

Beware of
coherent synchrotron radiation (CSR)!

very powerful microwave radiation
with λ >~ bunch length if
bunch length << size of vacuum chamber



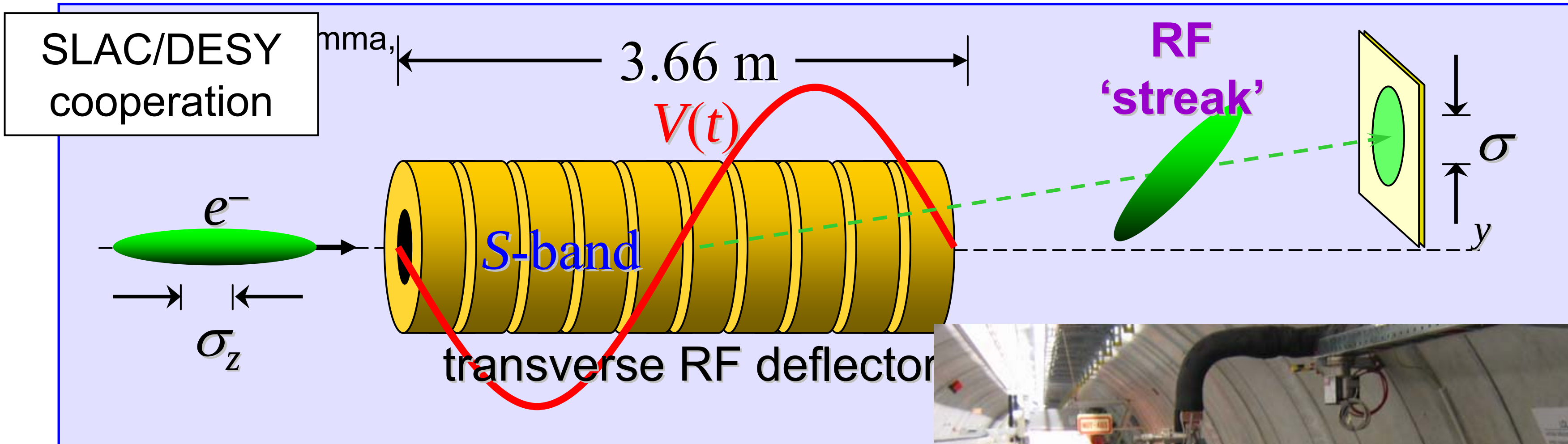
Longitudinal bunch compression

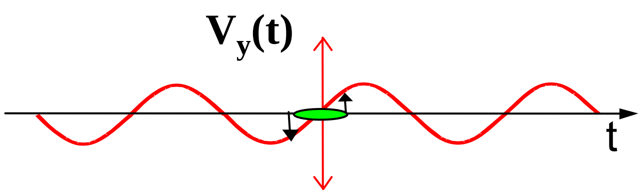


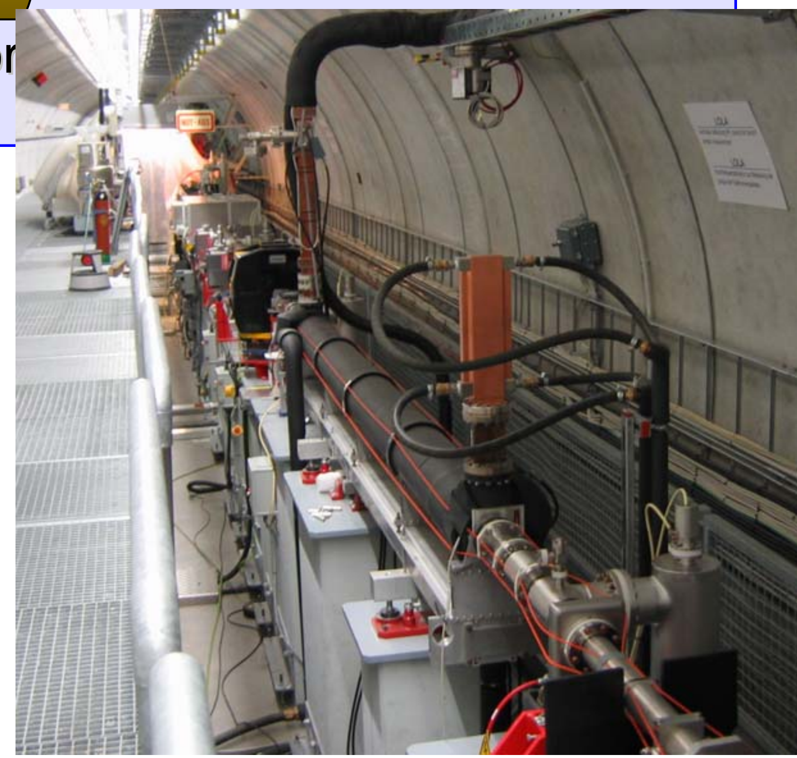
- Very complicated beam dynamics due to coherent synchrotron radiation
- Ultra-short photon pulses created ~20fs FWHM

Diagnostic Section at 130 MeV

Bunch Length with LOLA





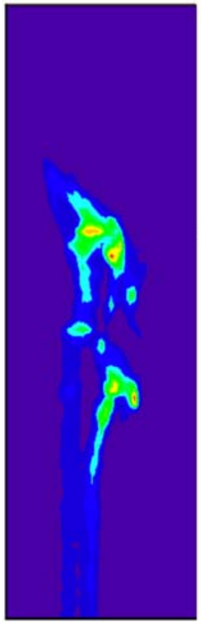


- Deflecting RF structure (S-band) from SLAC is used as a 'streak camera'
- Expected resolution < 10 um

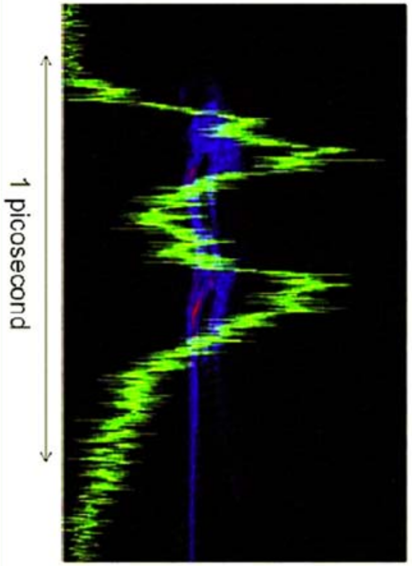
Pictures from LOLA

Three examples for different compressor settings:

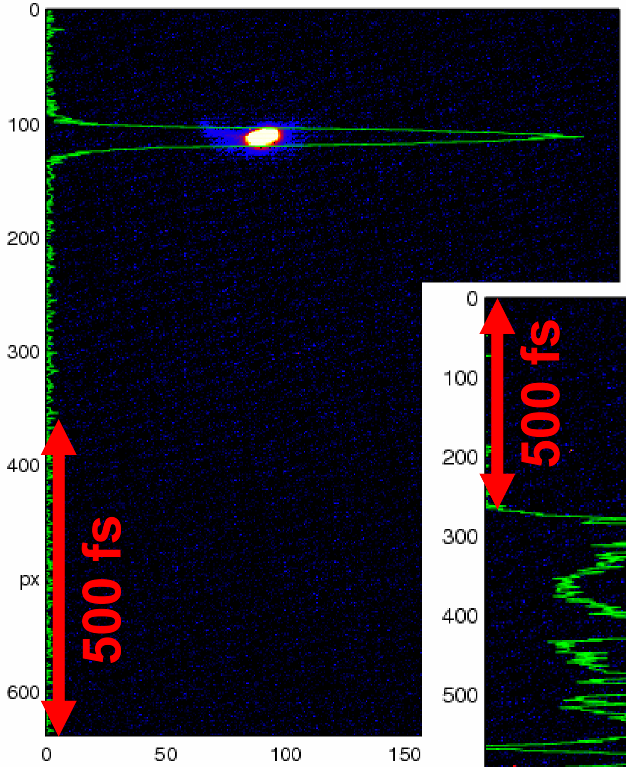
Resolution ~20 fs

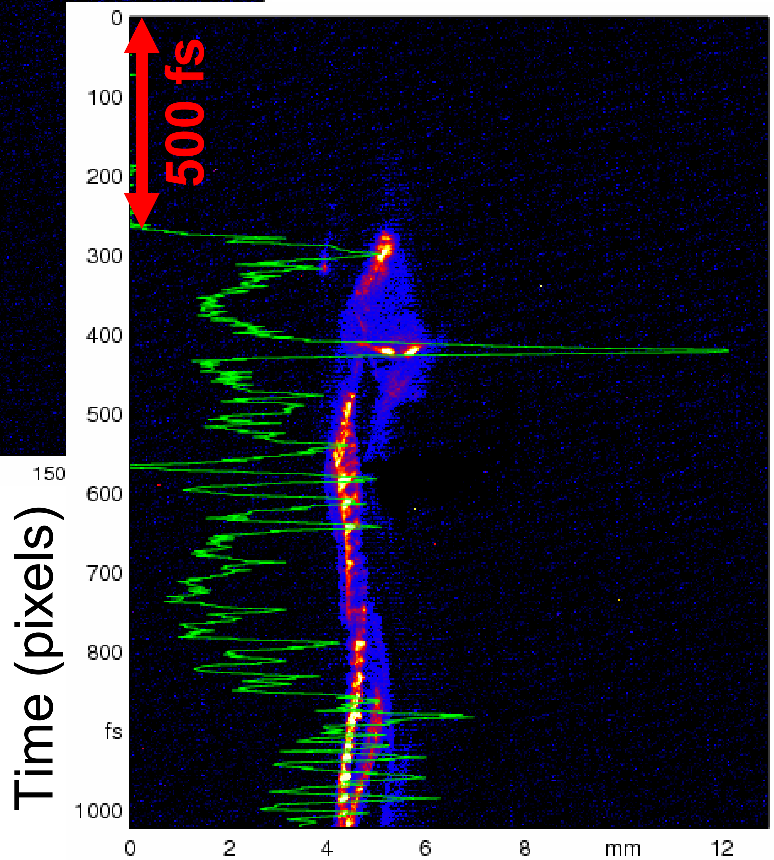


simulation

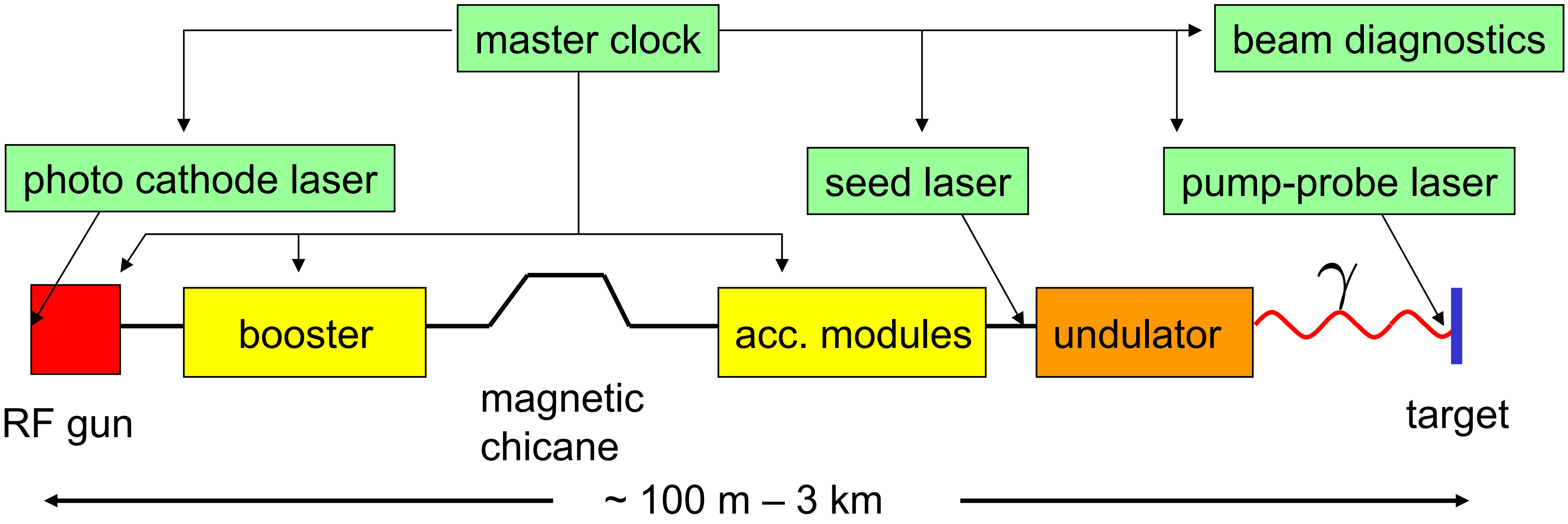


LOLA





Synchronization needed in a FEL facility



Many sources for changes of arrival-time of the FEL radiation !

Key Problem:

rf microwave oscillator is excellent master clock, but long-distance distribution of rf signals with cables is impossible at fs stability !

→ Work on an all-optical synchronization system

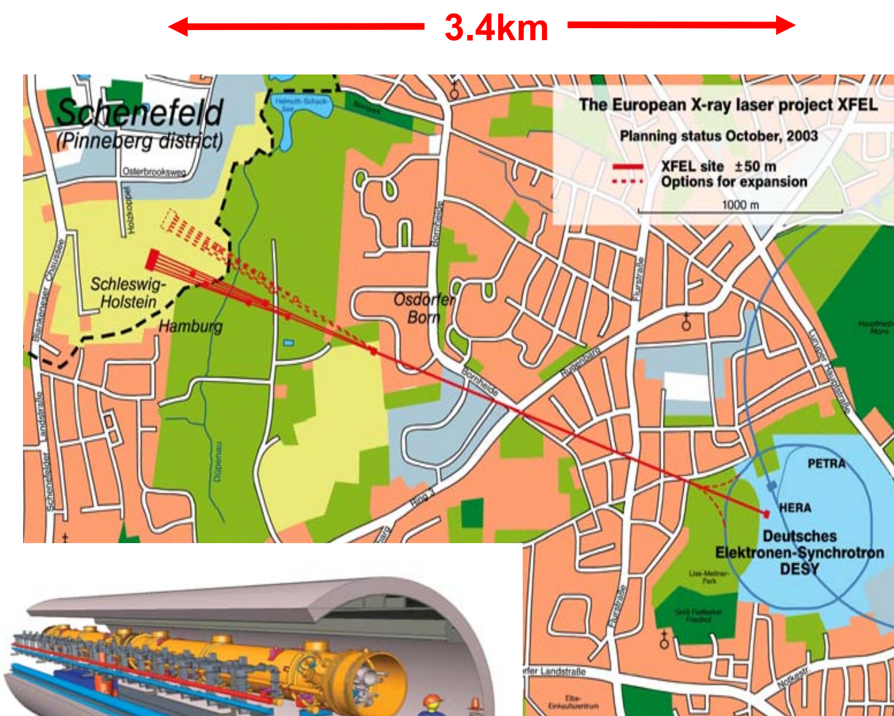
The European XFEL Project

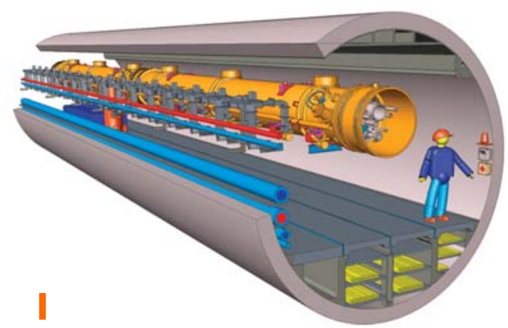
Site near DESY laboratory

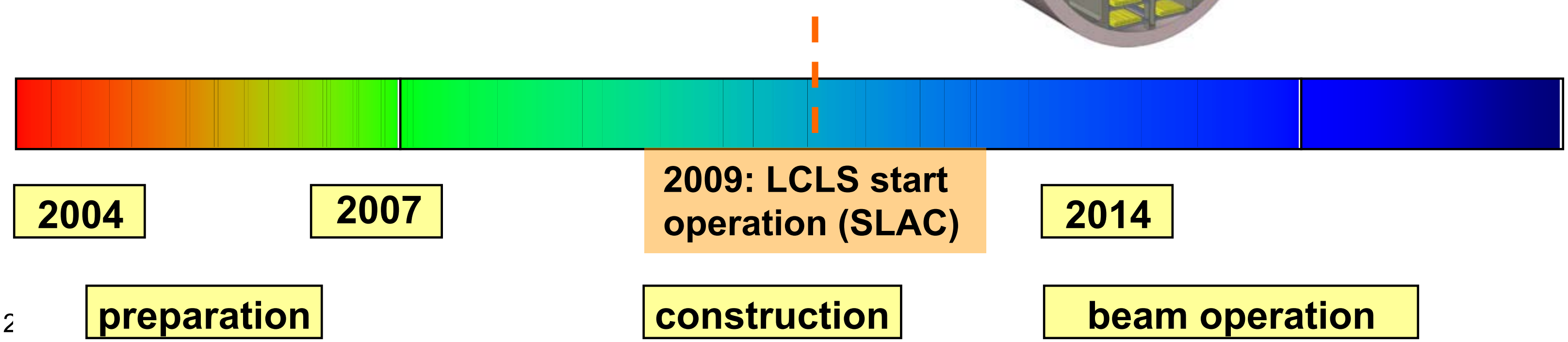
- Proposal October 2002:

  X-ray FEL user facility with 20 GeV superconducting linear accelerator in

  TESLA technology
- Approval by German government Feb. 2003 as a European Project
- German commitment for 50% of the funding plus another expected 10% by the states Hamburg and Schleswig-Holstein, 40% from European partners
- Total project cost 1056,6 **M€**

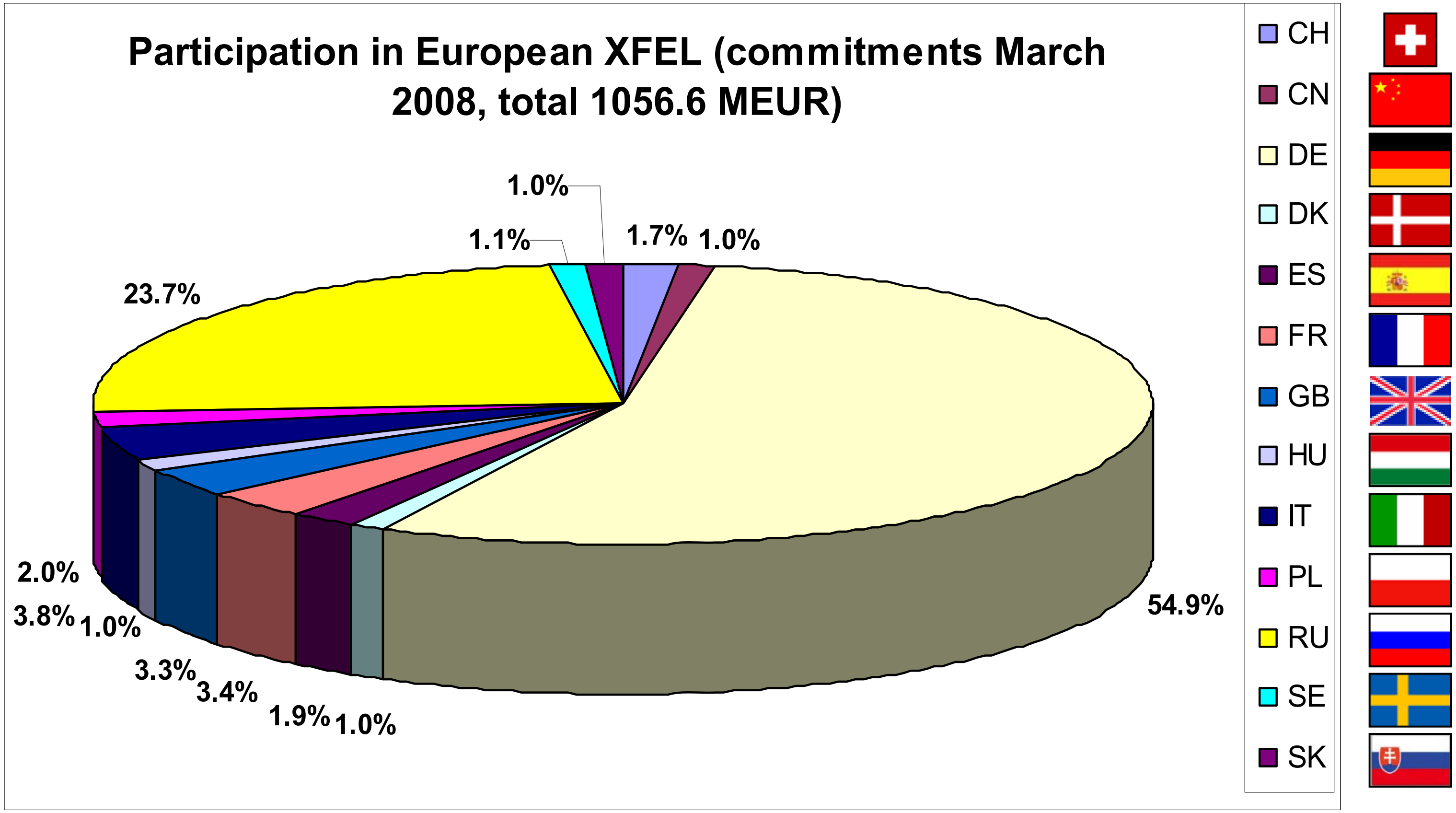






Status of financial commitments to European XFEL project

Includes ~90 M€ project preparation phase & commissioning
(contracts not yet signed ↔ minor readjustments may occur)



The European XFEL Company is in the process of being funded

The European XFEL

The European XFEL

XFEL Movie

Potential subjects for PhD work at FLASH/DESY, PETRA III and XFEL

1.Investigations on scenarios for “ultra-compression” or the European X-ray Free-Electron Laser (XFEL) to achieve bunch lengths < 10 μm rms, down to attosecond pulses. Beam dynamics studies, low charge options, “single FEL mode” options; if reasonable: tests at FLASH
2.Installation of coherent transition radiation screen in front of FLASH undulator. COTR measurements after installation of the 3rd harmonics RF system and comparison with LOLA and optical replica synthesizer.
3.Use of infrared undulator for longitudinal bunch profile measurements incl. investigations on micro-bunching instability in the visible and near infrared regime. Check dependency on machine settings, perform beam dynamics simulations. Potentially collab. with user group (Prof. Drescher). Comes in collaboration with 2).
4.Start-to-end simulation and control of electron beam dynamics after installation of the 3rd harmonics RF system at FLASH with and w/o seeding.
5.Experimental investigations on comparison of the FEL start-up process at FLASH either from shot noise or by High Harmonic Seeding
6.Multi-bunch effects at FLASH incl. stability of bunch center within bunch train & feedback.
7.Design and construction of a thermionic gun for LINAC II at DESY.
8.Options for High-Gain Harmonic Generation (HGHG) at FLASH and at FLASH II
9.High-resolution 6D phase space tomography at FLASH after installation of the 3rd harmonics RF system at FLASH, including impact on sFLASH performance (potentially MC-FEL program, in collaboration with LNF Frascati and MaxLab).
10.Development of a laser system for seeding and pump-probe at high rep.rate >=100 kHz (potentially MC-FEL program, in collaboration with BESSY).
11.Femtosecond synchronisation for FLASH and pump-probe experiments. Continue work of F. Löhl: Refine feedback stabilizing beam arrival time using beam arrival monitors after each compression stage. Include longer pulse trains.

At electron gun test stand PITZ in DESY Zeuthen:

1.Theoretical studies on electron beam dynamics in the vicinity of the photocathode
2.Cathodes for electron guns: new surface materials, new mechanical design (in collaboration with INFN Milano)
3. Relation between laser parameters and electron beam parameters (experiment and comparison with theory)
4.A two-frequency gun with or without a diode cathode (like PSI) for FLASH and XFEL.

CONTACTS: joerg.rossbach@desy.de, Tel. +49 40 8998 3617
shaukat.khan@desy.de, Tel. +49 40 8998 5492

The FLASH team

FLASH is a project within the TESLA Technology Collaboration